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**Effects of Bank Vegetation in Waterways with Special
Reference to Bank Erosion, Shear Strength, Root Density and
Channel Hydraulics**

By

Ivan Amarasinghe B.Sc.

**A thesis submitted to the Open University
for the Degree of Doctor of Philosophy
Biology Department
September 1992**

Author number: M7023041
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Abstract

This study quantifies the erosion of banks of a river which are subjected to an experimental regime of diverse vegetative parameters. The main aspect of research is a spatial and temporal analysis of erosion under banks with natural vegetation, a cultivated wetland grass, denuded banks, and banks under the initial process of secondary succession. Two major spatial components of a river bank are identified relating to the moisture profile prevalent at ambient flow levels. Comparisons are made on the rates of erosion during five temporal phases identified as of significance to riverbank erosion, prevalent hydrology and seasonality of plant growth in a temperate country. A process of slow but continuous undercutting in the toe-region of naturally vegetated banks devoid of semi-aquatic fringe vegetation is identified. An attempt is made to identify the effects on bank stability of colonisation of a bare bank by a wetland grass from seedling to maturity. The currently recommended practice of encouragement of secondary succession on banks is studied with comparisons on changes of erosion rates over a period of 25 months. Pioneer colonisers are identified. The effects of denudation on bank soil stability are monitored. A series of comparisons of erosion under the various vegetated and denuded banks are carried out in a range of possible permutations based on the defined spatial and temporal aspects.

A subsidiary study attempts to quantify the effects of bank vegetation of significance in civil engineering practice. The need to quantify the effects of non-structural modes of bank lining in terms of structural engineering terminology is identified. Bank shear strength in situ, its variation on the bank profile with variations of moisture content is studied. The role of roots of bank vegetation with special reference to possible effects on bank shear strength is addressed. It is concluded that there is no clear correlation between shear strength and erosion. Shear strength of the upper bank as measured in situ, by a shear vane, is reduced subject to a long period of submergence. The presence of bank vegetation may compensate for any reduction in shear strength in terms of critical bank stability. The need to identify other functions of roots, in relation to bank stability rather than shear strength alone, is identified. The presence of the phyllosphere as a skeletal yet effective physical barrier between the bank and the water is identified as the main negator of winter erosion on vegetated banks.

"The whole of science is nothing more than a refinement of everyday thinking"

Einstein, *Out of My Last Years* (1950)

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Chapter One

1.1 General Introduction and literature survey

The latter part of the twentieth century is notable for re-appraisals of scientific technology that have been administered over the last few centuries in the environmental development schemes around the world. One of the controversial subjects has been that of structural lining of stream banks (Brookes, 1987 & 1990; Hemphill and Bramley, 1989) and irrigation canals (Kouwen and Li, 1980). Mathematically acceptable, simplified laboratory based models fall far short from the expected results when they are applied to field projects (Chadwick and Morfett, 1992). Hence with time, both channel geometry and observed flow regimes in both main and subsidiary channels deviate considerably from those expected and predicted by the project consultants (Kraatz, 1977 ; Bowie, 1982).

Bowie states that by 1968, the estimated erosion of 480,000 km of streambanks in the United States produced approximately 450 billion kg of sediment each year. The computed yield of sediment from channel bank erosion in northern Mississippi was 1,050,000 kg/km per year. By 1969, the financial estimate for the cost of preventive treatment for 238,000 km of seriously eroding streambanks was approximately \$420 million annually.

While the problem in the rich countries is one of allocation of national funds in regional developments, the poor countries are borrowing money from aid-donor organisations such as the World Bank and the International Monetary Fund for innovative national projects. Application of structural measures of bank protection to their waterways and irrigation canals is a priority in the wake of their attempts to irrigate land and to maximise food production. The situation is compounded because of borrowings not only for repair work to existing river-banks and irrigation canals but also lining the new extensive irrigation canal network systems. For example, Sri Lanka which has a historically proven excellence in irrigation technology over the last 3000 years (Brohier, 1934; Dikshit, 1986; Fernando, 1982; Mendis, 1985 ; Paravithana, 1958; Seneviratna, 1989) has turned to new civil engineering technology over the last few decades (Mendis,

1989a &b). S. Dimantha, Deputy Director of the Irrigation Department of Sri Lanka (personal communication) states that however much the ancient traditional systems are proven as efficient, the credibility lies not in proven efficiency but in the interpretation of the ancient technology in current scientific terms. Foreign aid is a *sine qua non* for their development projects.

The central dilemma is that all financial aid for development work is subject to plans and structural applications recommended by the aid-donor organisations. Whereas in the traditional systems, the raw material used and the work-force was local, the new technology entails total importation of both structural raw materials, consultants and contractors who in turn are recommended by the aid-donor governments. In the majority of cases, interest payments for the aid and loans are carried over the next half century at least. However there is no guarantee of the success of the enforced plans and structural applications such as bank linings (Kraatz,1977). Robinson et al (1990) discuss the geomorphological aspects and demonstrate the socio-economic consequences of flooding as relevant to southern Britain. From a global conservation aspect, Boon (1992) discusses the case for river conservation as an issue of contemporary global importance. He identifies the threefold aim of the World conservation Strategy (International Union for Conservation of Nature and Natural Resources, 1980) as follows:

- i. To maintain essential ecological processes and life support systems;
- ii. To preserve genetic diversity;
- iii. To ensure sustainable utilization of species and ecosystems.

Such an anthropocentric approach should be adapted to what Boardman (1980) argues as the need to encompass issues affecting human welfare and indeed to ultimate socio-economic structures. In this study, it is hoped to consider the relevance of such an argument on the basis of the results obtained.

1.1.1 A summary of methods of erosion control on channel banks

Historically channel bank stability has been ensured by the use of three main groups of raw materials :

- i) the natural building blocks associated with the 'pre-industrial revolution era'; These vary from stones, boulders, clay soils to other materials such as coconut husks.

ii) the use of artificial structural (civil engineering) building blocks of the 'post-industrial revolution' era; they are materials such as plastic netting, gabions, and metal structures to re-inforce soil;

iii) use of appropriate techniques of a non-structural nature (see Table 1.1); for example, appropriate bank vegetation has been used as a non-structural mode of soil stabilisation around the world; in addition there is increased interest in the substitution of biodegradable, 'eco-positive' material such as jute fibre (Trade name: Geojute) and coconut fibre, in preference to synthetic fibres such as Netlon. In the technique using Geojute, the bank is repaired or constructed with a woven jute net laid over to prevent erosion of the bank soil. Appropriate bank vegetation cover is either encouraged through natural revegetation or artificially induced by seeding. As the jute fibre disintegrates enriching the nutrient value of the soil, the consequent stability of the bank is dependent on the vegetation. Similarly, a range of coconut fibre based bank liners are used globally.

At present, there is a revival of interest in non-structural techniques with special reference to bank vegetation. This arises directly as a result of the applicable advantages to various environmental, ecological and socio-economic aspects in different societies around the world (see 7.5). The theoretical aspects of using vegetation as a channel bank liner (Ree and Palmer, 1949; Ree, 1958; White, 1988) have profound implications on many scientific disciplines. For example, the suitability and efficiency of various plant species as tested in terms of terminology used in physical sciences, i.e. increase in soil shear strength, reduction of erodibility of the soil and resistance to the channel flow. Such quantifications are made with the objectives of understanding the operative system/s and the development of applicable predictive models of flow. From a multi-disciplinary aspect, controversy may arise on many fundamental aspects such as the validity of soil shear strength as the main criterion for soil stability. As such bank vegetation as a channel liner poses new and challenging aspects for research and development.

It would be an over-simplification to expect bank vegetation as a panacea for the problem of bank erosion. As De Ploey (1981) argues there may be disadvantages such as the added pressure (surcharge) to the bank slope brought on by the weight of vegetation such as trees. Such apparent disadvantages have to be addressed specifically in terms of

choice of species as bank liners for specific service requirements taking into account bank slope, soil composition, hydraulic variations, sinuosity and the river/channel regime (see 1.4.5). While it was traditionally accepted that vegetation on slopes contributed to the stability of the slope it was only in the last few decades that scientific research was carried out in terms of civil and hydraulic engineering terminology (Siebert, 1968; Simons et al, 1979; Bowie, 1982; Gray and Leiser, 1982).

Non-Structural	Structural
1. Flattening bank slopes	1. Rock riprap
2. Control pool fluctuation	2. Transverse dikes
3. Vegetation	3. Fences
4. Limit recreational boating	4. Gabions
5. Do nothing (Natural Stabilization)	5. Grouted rock
	6. Sack revetment

Table 1.1 Summary of stabilization measures (Simons et al, 1979)

Of the non-structural measures, two measures involve the establishment of vegetation. The first is that of direct 'introduction of vegetation' while the second is indirect encouragement of natural re-vegetation by 'doing nothing' (see Table 1.1). In ecological terms the former is an artificial (cultivated) ecosystem while the latter is 'secondary succession' which is an essential component and concept in natural ecosystems. There is a need to understand both these measures in terms of a deeper scientific evaluation of the advantages and disadvantages of such practices. The first step in such a process is to understand the variety, complexity and appropriateness of bank vegetation for its proposed service as an efficient bank liner.

1.1.2 Bank Vegetation

The distribution of plants in semi-aquatic and aquatic surroundings has been discussed in depth by many authors. Arber (1920) was a pioneer on aquatic macrophytes with reference to plant structures and their adaptations to life in the water. Tansley (1949) in his classic treatise on "The British Isles and their vegetation" deals with how and why plants grow in certain places and not in others. Butcher (1927, 1933) described

different types of stream vegetation and the importance of currents, soil, shading, etc. in forming plant communities. Westlake (1967) studied the productivity of aquatic macrophytes under low velocity currents. Whitton and Buckmaster (1970) and Haslam (1971, 1978) have carried out careful surveys of river vegetation. Haslam (1978) in particular looks into the aspects of varying river hydraulics, and their effects on both aquatic and semi-aquatic bank vegetation. Different species of plants have been studied with reference to the hydraulic resistance to flow, rooting depths, susceptibility to erosion, anchoring strength and effects of sedimentation. Hooke (1986) investigated the types and modes of colonisation of sand banks by vegetation and their implications for river hydraulics.

The central problem is one of applicability of the theoretical finding into the field situation for the desired result. What this implies is that a species of plant that is the recommended choice for a particular service requirement (eg. planting *Salix nigra* to prevent undercutting or seeding *Lolium multiflorum* to prevent upper bank failure of a bank slope as recommended by Bowie, 1982) may be disputed. Why should a tree species be planted at the toe-region while grasses are recommended for the upper bank? Tree species such as *S. nigra* may be associated with banks of waterways. But they may cause more complications through the formation of considerably powerful secondary currents due to their rigid, structural nature if they are planted at the toe-region. In time they may cause serious undercutting of the banks. It may be more appropriate to choose herbaceous semi-aquatic vegetation in this region. The reasons for such a choice are based on evolutionary attributes as discussed in 1.4.1. Such arguments necessitate a better understanding of the spatial distribution and positioning of bank vegetation as a solution to the primarily geomorphological and hydraulic problem of bank erosion. There is a marked lack of scientific literature available in this area of crucial importance to fluvial geomorphology.

The other aspect is one of applicability of plants tested under laboratory conditions that may prove to be a failure in the field situation from a temporal aspect. A host of ecological factors such as interspecific competition will determine the long-term success in establishment and plant demography. The theoretical findings, which are based on

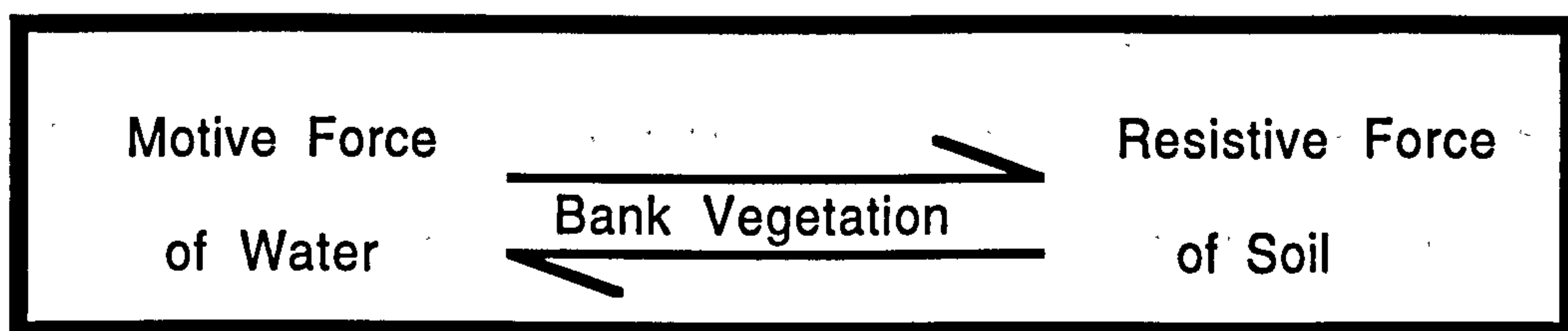
limited complexities such as controlled laboratory conditions, carry with them the inherent limitations in applicability under field conditions. Hence, the almost universal controversy surrounding most laboratory tested models (eg. roughness coefficients in hydraulics, self thinning laws in plant biology) which deviate from the expected results in the field. For example, Silvertown (1987) discusses the ecologist's dilemma of identifying the 'realised niche' as opposed to the 'fundamental niche' of plant species on river banks and expresses concern over the practical limitations in the field as opposed to theoretical deductions.

The above mentioned factors make it imperative that recommendations on plants as bank stabilisers must be made through a theoretical understanding of plant biology and their applicability in the field situation as tested in field experiments.

1.1.3 Role of vegetation as a primary mediator of the bank-water interaction

The central question is whether different species of plants have naturally evolved as the main natural intermediary between the motive force of water and the resistive force of the bank soil. If there is sufficient reason to believe that the evolutionary process led to specific adaptive attributes to different species of plants, then it would be reasonable to presume that those species in turn were adapted in such a manner that their habitat would be conserved. Failure to have such reciprocal abilities would be detrimental to the survival of the species. For example, Turmanina (1965) discusses the role of specially shaped roots on species of trees on soil slopes and stream banks with reference to their probable role in soil conservation.

The emphasis so far, on the two component system of interaction (soil - water) may be due to the lack of depth of perception of the role of plants in the operative system. It may be worthwhile to investigate the soil-water interaction with bank vegetation as the intermediary which determines both the intensity and the result of the interaction.



Yet, it is difficult to allocate the role of vegetation as an intermediary alone because the vegetation itself is affected by the other two principal components of the interaction. In addition, by virtue of its adaptive strategies, vegetation not only mediates as an active member of the interaction between the soil and the water but utilises both of them in demography and reproduction (see 1.4.1). While the direct significance of the adaptive strategy is for the survival of the plant in a hazardous environment, there are aspects of subtle but crucially significant outcomes to the stability of this dynamic ecosystem. The most important is the ability to physically mediate as a barrier between the two interacting components (soil and water). In essence, the bank vegetation forms a buffer zone which absorbs a considerable amount of the motive force of the channel flow which would otherwise have acted directly on the bare bank and eroded it. Therefore, it is questionable whether bank vegetation should be treated as a subsidiary of the operative system/mechanism of the process of erosion or as an equal, if not the key component of a three component ecosystem.

Reasons for incorporating vegetation as a subsidiary component in models developed so far (see 1.4.3a and 1.4.3b) may be that : (a) these models were developed by civil engineers who needed to account for the roughness of the channel banks not exclusively for vegetation (concrete and other linings were prioritised over vegetation); (b) it was identified that incorporating vegetation as a main intermediary will necessitate complexities that may not produce a simple model (such as Manning's or Darcy Weisbach's) that will suffice the then contemporary 'structural' developments.

1.2 An ecosystem approach

1.2.1 An alternative appraisal of bank erosion : As much as a scientific understanding of one factor (eg. soil or water) on plants is in itself valuable, it may perhaps be useful to attempt to understand the many factors operating in complicated,

multifaceted interrelationships in an environmental system. Trudgill (1988) discussing soil-vegetation systems states, "our traditional reaction is to be dissective and to break down environmental processes into small, defined compartments in a specialist manner, or to look at systems in a broad generalist manner. The first focusses on selected items and ignores other specialist details, the second looks only at the broad main relationships and ignores subsidiary details." The dilemma is whether to identify the wood from the trees or vice versa. Most laboratory studies adopt the former approach which lead to reductionist conclusions. But, recently there is a more holistic approach taking into account the variety of other factors that prevail in the field situation. For example, Hey and Heritage (1988) discussing dimensional and dimensionless regime equations, argue for more theoretical accountability for the variety of generalist factors prevalent in the field. There is a necessity for quantification of more parameters which are at present allocated coefficient or constant values in mathematical models. The essence of the argument is that there has to be an optimal medium between extreme reductionist mathematical models and futile attempts at incorporation of the total complex of variable factors operative within the system.

However, while recent arguments identify the position of importance of vegetation on the banks in direct relation to erosion (Simons et al, 1979; Zimmermann et al, 1981) and regime geometry (Thorne et al, 1988), there has been no satisfactory specialist study that encompasses the concepts of ecology or those factors considered to be of significant importance by plant biologists (see 1.4.5) such as secondary succession, seedling establishment and demography. The problem of bank erosion in waterways has so far been addressed with the emphasis on bare banks. The result has been excellent discussions on the mechanics of soil erosion caused by such factors as frost action (Walker and Arnborg, 1966; Lawler, 1986), precipitation (Hooke, 1977a), wave action in lotic waters (Hey, 1987) and of course the vast literature on the empirical, laboratory and field studies on lentic waters. As authors such as Hooke (1977a) suggest, a study of erosion under vegetated banks is overdue.

As mentioned in 1.1.2 above, the central dilemma is, could one ignore vegetation *per se* as a subsidiary component of the river regime? The answer is critically important in terms of the mechanism operative in the system. To identify the extent of importance of

vegetation in the river regime, one has to identify the effect of bank vegetation in relation to the other major components of the system i.e. water and soil. Vegetation affects flow of water in the following aspects :-

- i) Velocity of flow: mainly the primary isovel;
- ii) Boundary shear stress: has the potential to create new secondary flows as well as modifies or negates the shearing stress of secondary flows arising from other morphological features of the stream or river such as bends ;
- iii) Roughness: a universally identified factor that has been a main obstacle to formulation of accurate predictive equations and models over the last two centuries; (see 1.4.3b for further details)

Vegetation affects the bank and its soil on the following parameters:-

- i) Soil cohesion;
- ii) Soil erodibility;
- iii) Soil moisture content;
- iv) Effective hydraulic radius of the channel;

These parameters are further discussed with references in 1.5. later.

1.2.2. Identification of Components of the Ecosystem

The fundamental components (see Fig.1.1) are :

A) water, B) soil, C) vegetation.

What is important is the stability of the ecosystem in the long term, even though the ecosystem itself is dynamic due to the changes in the main components and subsidiary components. What governs that long-term as well as the short-term stability are the critical points in changes of quality or quantity in one or more of the components. For instance, if a species of plants was to be cultivated (see Ch.4 for *P. arundinacea*) on bare or eroding banks, at what stage (temporally) will be reached the threshold of long-term stability, imparted by the plants on the banks? The possibility of short-term bank stability during establishment of seedlings if they get washed away with their rhizospheric soil in a subsequent high flow has to be studied (see 4.5.2a).

The flaws arising from ignoring the diversity of bank vegetation for the sake of simplicity in formulating a mathematical model, have been well confirmed by authors

such as Thorne et al (1988) in relation to the river regime theory and bank vegetation types (see 1.4.5). A further complicating factor may arise out of accumulation and gradual incorporation of decaying plant debris such as fallen leaves on the bank soil. The fact that variations of shear strength in a soil type can arise due to accumulation of different levels of leaf litter has been proven for agricultural soils (Ohu et al, 1986). This can eventually lead to changes in soil composition and its erodibility when subjected to fluvial forces.

1.2.3 Development of a model

The fundamental questions that arise are:

(i) Can water act as the independent factor affecting both bank vegetation and bank soil?

i.e. (a) plants (for their establishment and survival) and

(b) the bank soil (for its stability) as dependants?

This research project addresses (a) above, as previous authors have addressed (b).

(ii) Could the critical limits of hydraulics be identified for the stability of a given bank with a given vegetation? (see Experiment 1 for mixed natural bank vegetation, and Experiment 2 for a cultivated monoculture);

(iii) Are there self balancing stable fluvial ecosystems? (see Experiment 3 on natural re-vegetation)

(iv) What roles do different species of bank vegetation play in determining the stability of the bank in particular and the ecosystem in general? (The latter may be of significance in relation to the current environmental legislation.)

In addition, there are a multitude of questions that arise from the probable aspects of quantification of the subsidiary components of the model. For instance, erodibility of the soil has to be studied concurrent with discharge parameters, tractive force of water, soil particle size and bulk density to name but a few factors.

At this stage of inquisition, the simplicity of the three factors transcends to a more complex and ramifying stage (Fig.1.1). It is best to identify the inter-relationships between and within the three major components and in turn the physical stability of the

system in this study. Such a study should explain whether vegetation does present such importance as to be treated as a fundamental component in initiation, increase or decrease of bank erosion under varying fluvial conditions prevalent in a small river. Certain subsidiary factors (see Figure 1.1) such as shear strength, moisture content, soil type will be quantified. An extensive study of all the subsidiary factors is beyond the scope of this study. It would need a team effort with considerable resources of technical assistance and equipment to compile a database that encompass the main as well as the subsidiary components of this dynamic ecosystem.

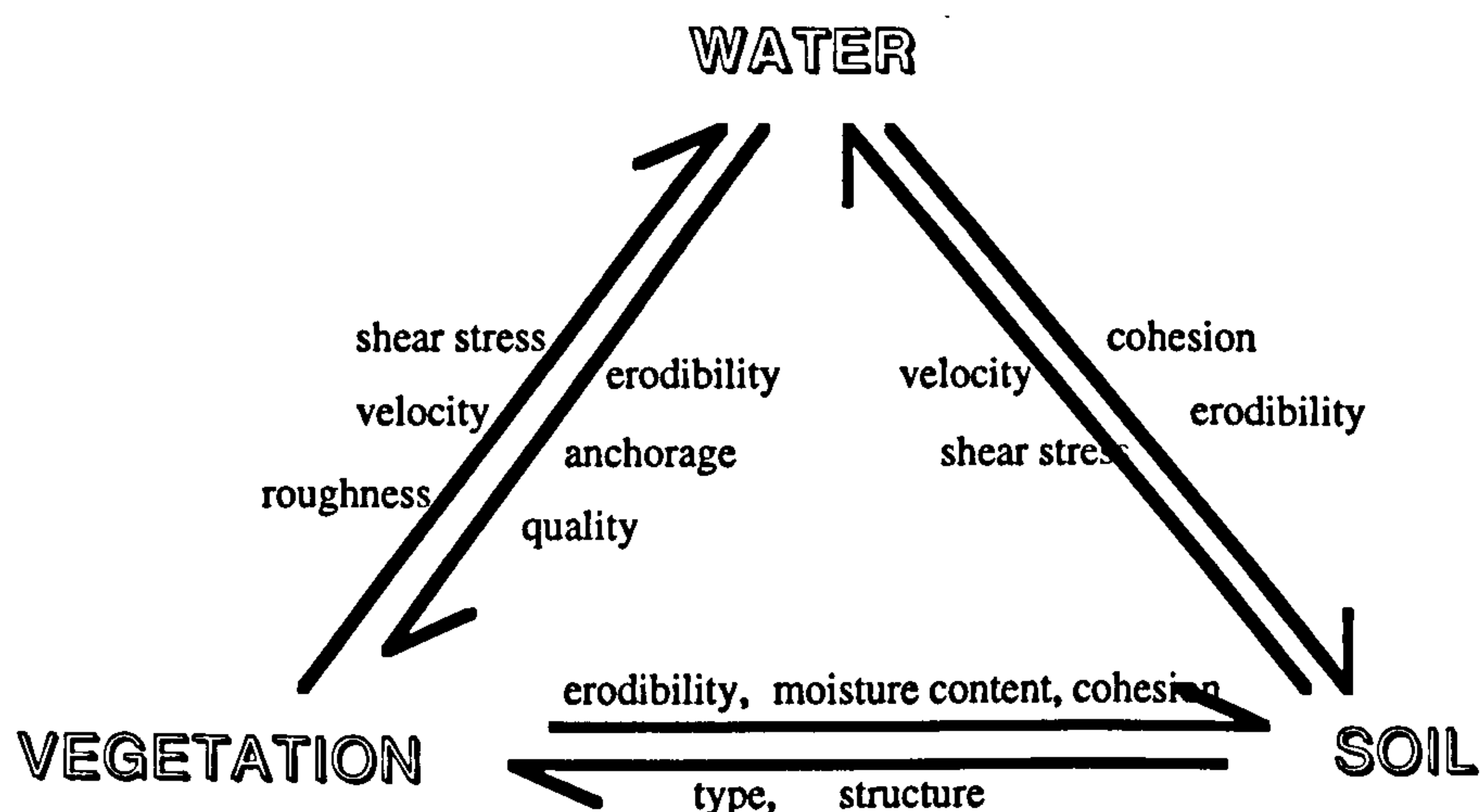


Fig.1.1 : Proposed model of interactions of the principal components of the ecosystem

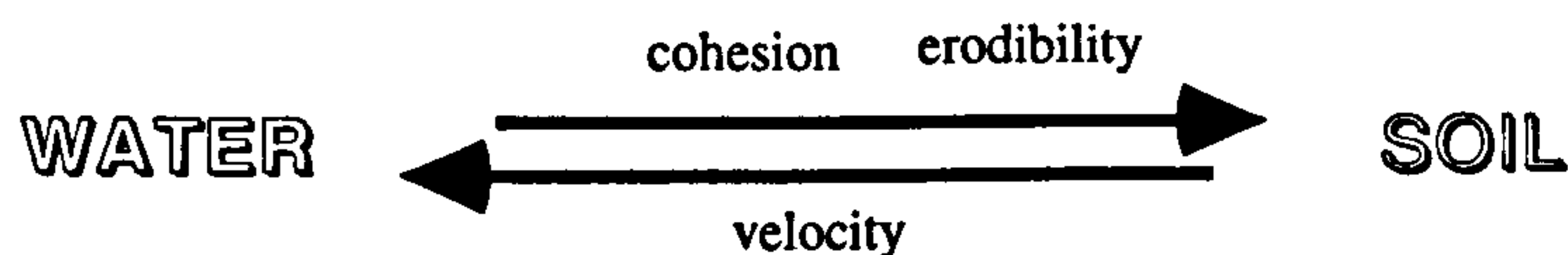
The dilemma of current scientific demand for modelling as an essential component of a research project by the modellers and the probable inappropriateness of polarising the scientific community into 'modellers as opposed to 'experimentalists' is discussed in depth by Boardman et al (1990). They identify three major reasons for "sub-optimal" performance of a model, viz: constraints of data availability (discussed above) including indeterminate problems of accuracy and precision; constraints imposed upon independent tests of any models developed from a given database; unlikelihood that any model developed from a database will elucidate the complete nature of controls or dynamics of the process and transfers involved.

Of the above three reasons the matter of constraints in data, accuracy and instrument precision shall be discussed in 2.3.3, 2.3.4, 2.3.5 and 2.3.6 as applicable to this research project. The literature survey reveals the paucity of both intensive as well as

extensive research work carried out on the relationship between shear strength and root density on riparian vegetation. Ideally the model developed must account for the seasonal variations (i.e. temporally extensive) of both live root density as well as soil moisture content variations (i.e. spatially extensive) associated with changes in channel hydrography. It should also be noted that the diversity of riparian species is extensive. As the rooting characteristics are so diverse (tap rooted, fibrous, rhizomes and tubers) the root sampling should be intensive irrespective of the damage it may cause to the bank. Any assumptions of a uniform distribution of roots within a cylindrical volume of bank soil would only suffice a mathematical model and hence inapplicable in the field.

The validation of a mathematically feasible and laboratory testable model which would have to account for numerous field variables (see Fig. 1.1) by assignment of coefficients and constant values, was superseded in this study by an accentuation of process identification aspects of erosion and the functional aspects of vegetation in the dynamic river bank ecosystem. The author preferred to address a more broadbased field project with a lateral research orientation. This was to encompass a series of experiments which addressed the problem of bank erosion under varying hydraulics and different vegetation types. In essence the concept of modelling as 'the essence of contemporary research' is compromised for the sake of "scientific explanation". This approach is in fact that recommended by Boardman et al (1990) in their discussion of the difficulties on "the degree to which modellers and field scientists (should) collaborate over solving erosion problems".

1.3 Relationships between water and soil, in bank erosion



1.3.1 Hydraulic Action:

The shearing of bank material by hydraulic action at high discharges is a most effective process (Hooke, 1977a & b), especially on non-cohesive banks and against any projections from the banks (Thorne, 1978) including bank overhangs. Local turbulence

characteristics and shear stress distribution play a major role in determining the initiation as well as the subsequent process of erosion (Knighton,1973). Simons et al (1979) estimated that flow forces were at least six times more effective than any other process in their study of the Connecticut River. This study is based mainly around the same motive force of flow induced bank erosion.

Two main processes of significant importance in fluvial erosion of banks (Knighton,1984; Simons et al.,1979) are :

- (i) near-bank erosive forces acting as waves generated by wind and boats;
- (ii) undercutting at the base of the banks: A factor of significance is that velocity and boundary shear stress are at a maximum in the lower region of the banks even when the flow is bankful (Bathurst et al,1979; Simons et al,1979). A critical review and analysis of undercutting at the toe region is presented by Thorne et al (1988).

1.3.2 Slumping: Wet bank slumping (Twidale,1964) and subsequent bank retreat (Klimek,1974; Hooke,1977a &b, 1979) take place following a high flow or flood event of short or long duration. Bank stratigraphy (see 1.5) plays a crucial role in slumping consequent to lower bank undercutting over a period of time (Thorne,1978). Klimek (1974) observed that in the River Wisloka, water percolating through the basal region loosened the sandy gravel and liquefied the lower parts of the overlying silty clay thus inducing slumping of the majority of the bank surface.

In fact, this process of erosion of banks is described as a pseudo- cyclic process (Knighton,1984), where undercutting, upper bank failure and removal of failed blocks occur in that order. The emphasis of this inter-relationship of processes has been observed earlier by Stanley et al.(1966).

Brookes (1992) identifies the possibility of deepened reaches that may be formed by high energy discharges downstream which may function as a trap for gravel sediment arriving from upstream. He suggests that this process is followed by bank slumping.

1.3.3 Rotational Slipping: This occurs when repeated failure along surfaces roughly concave to the slope causes the development of a multifaceted bank profile. Water acts as the causative agent in that the profile of moisture content on the bank plays a

significant role in this event. Terzaghi and Peck (1967) present an appropriate discussion on rotational slipping in mass failure. As this research study does not encompass such mass failures it would be irrelevant to detail the mechanism or propose any possible developments on current theories.

It has to be mentioned that most explanations of the shearing resistance offered by root permeated soils in prevention of soil erosion are based on rotational slips (Waldron, 1977; Waldron and Dakessian, 1982 and Gray, 1978). Such explanations depend more on intrinsic properties of roots in terms of tensile strength than any physiological processes such as transpiration.

1.3.4 Frost Action: Walker and Arnborg (1966), observed that the growth of ice crystals and ice wedges due to frost can cause bank instability. The process is one in which frozen water (ice) can widen pre-existing cracks, disaggregate surface material thus preconditioning the bank to subsequent erosion in warmer weather and hydraulic flow. Lawler (1986) stresses that while fluvial or hydrological factors seem to control the area of bank eroded, the amount or intensity of erosion is largely determined by previous cryergic activity. However, this need not necessarily be universal as most of the fluvial erosion occurs in tropical countries where there is no such frost action. Perhaps this process of frost action needs further research as to whether it is dependant on a soil type or other significant intrinsic factor/s of the bank.

1.4. Relationships between water and bank vegetation

Bank vegetation in Britain is highly diverse both taxonomically and with respect to morphology and size (cf Holmes et al, 1972 and Holmes and Whitton, 1975, Haslam, 1978). A literature survey on the relationship between bank vegetation and water indicates that the approach to this subject should be categorised within currently defined academic disciplines. Each discipline tackles the relationship within its own limitations.

1.4.1 Water and Bank Vegetation - an ecological overview

From ecological and plant biological perspectives this relationship covers a vast spectrum of concepts and physiological processes. Of the ecological concepts, plant demography and competition play key roles on the positional preference of different

species on the bank upwards from the waterline (see Fig. 6.1). Two demographic processes i.e. survival and reproduction play the key roles which determine the 'fitness' (Silvertown, 1987) of the species in terms of relative evolutionary advantage.

Harper et al (1992) discuss the necessity for use of river bank habitats as the building blocks of conservation. As such there is a need to study the effects of bank vegetation as a primary component of river bank conservation. The argument has to be that if the bank vegetation cannot conserve its own habitat (the river bank), then it will be uprooted by floods. Hence there is a need to conserve the bank vegetation first, if they are to be used as building blocks for riverine communities of ecological significance and conservation values.

Davey et al (1990) address the need to research into the genetic variation and adaptation to flooding in plants. They accept that some of the morphological and physiological characteristics that enable certain higher plants to tolerate or avoid the effects of flooding are understood. Yet they express concern on the much needed lack of understanding on plant fitness, selection and other evolutionary forces. As they state the ability of contemporary vascular plants to inhabit hypoxic soils is a response to selection pressures over 400 million years. A need for a mechanistic study of growth form and life history that appear beneficial to flood tolerance is identified.

Within the species of plants that show preferential positions on the bank slope (Haslam, 1978) shown in Figure 6.1, it is considered best to discuss three commonly observed species in terms of their relationships to the changes of the hydrograph in the channel. They are (i) *Phalaris arundinacea* (Reed Canary grass), (ii) *Urtica dioica* (Stinging Nettle) and (iii) *Epilobium hirsutum*. (Great Willow Herb). This thesis is concerned mainly with (i) and to a lesser extent (ii) and (iii).

Since according to Haslam (1978), the preferred habitat of *Phalaris arundinacea* is on the waterline/lower bank, it is presumably better adapted to this habitat than are the other two species. As Grime (1977, 1979) postulates "competition has been associated with the evolution of a distinct strategy based on characteristic and measurable genetic attributes which facilitate the exclusive occupation of the preferred habitat". In essence, waterways have been directly linked with the phenotypic as well as genotypic evolution of

Phalaris arundinacea . On the other hand, *Phalaris arundinacea* tolerates dryland habitats also (see 4.1b). As such, the question arises as to whether this species establishes first on the upper banks and is consequently competed out by species such as *Urtica dioica* and *Epilobium hirsutum* which are efficient competitors that do not prefer the waterline as a habitat but may yet survive short-term bankful or sub-bankful flow within the channel.

The positional effects at the bank-toe region, for *Phalaris arundinacea* as a semi-aquatic plant, pose the question of adaptive strategies to prevent it being uprooted by high flows as well as being subjected to waterlogging through both summer and winter. Both high flows and waterlogging affect survival and reproduction. In terms of reproduction there is no literature available on the fate of the seeds that alight on, and any seedlings that may sprout at low flow periods on the bank toe-region. Where survival is concerned it would be appropriate to see the seedling establishment on the upper, drier regions of the bank and follow the progress of the cohort downwards to the bank-toe region. This progress will be reflected both in the above ground parts as well as the below ground parts (i.e. shoot density and rhizome plus root density) at different levels of the bank from seedling formation to maturity and vegetative reproduction. Another aspect is to test whether it will act as a better toe-protector of the bank at high flows, in comparison with other species. This will be reflected in root density studies and shear strength measurements (if shear strength is the correct measure of bank soil stability). In effect, such a study will address not only aspects of direct geomorphological significance but also ecological significance.

A similar study on natural bank vegetation on the mid to upper bank region of a river should throw light on the responses to stress and disturbance caused by changing hydraulics within the channels, for *Urtica dioica* and *Epilobium hirsutum* which form a significant component of this bank region of lowland British rivers. Whether these would show adaptive architectural strategies for survival during submergence is not clear as they are mainly dryland plants. However, Grime et al (1986) comment that they are prevalent on the banks of waterways. The distinction between *U. dioica*, *E. hirsutum* and *P. arundinacea* is that the former do not invade into the waterlogged, bank-toe region while the last (*P. arundinacea*) is invasive within the channel up to a metre from the bank-toe. A

comprehensive bibliography on adaptive architecture with special reference to rhizomatous plants is presented by Bell and Tomlinson (1980). Stinging Nettle (*Urtica dioica* L.) and the Great Willow Herb (*Epilobium hirsutum* L.) may utilise the temporary force of adversity to their ultimate advantage as do all water plants. The branches that are torn off by storm flows act as propagules for the dispersal of the species down the stream by lodging and establishing themselves in new habitats (Haslam, 1978).

As shown in the above examples riverbank plants have diverse strategies to counter stress and disturbance. These may be more important to their survival than the mere increase of root density. What is more important is the fact that not all plants are capable of these strategies. If the hypothesis that increase of root and rhizome density increases shear strength of the soil (Endo and Tsuruta, 1969; Waldron, 1977, Waldron and Dakessian, 1982) holds true, then it should be applicable to the river bank soil as well. Concurrently, such increases in shear strength of the bank soil should reduce bank erosion at different discharge levels. If the above relationships are evident in this study it may prove that one of the key aspects of these organs is increase in bank shear strength thereby increasing bank stability.

If on the other hand roots and rhizomes do not necessarily increase the shear strength of the soil but yet the presence of vegetation reduces or negates bank erosion then there is sufficient reason to believe that an unknown factor/s (attributable to vegetation) is responsible for this. In the latter case, future studies should be directed at adaptive strategies of plants in prevention of bank erosion because the above examples clearly indicate the importance of evolutionary attributes and adaptive strategies.

By 1988 (see Thorne et al, 1988 and the discussion in 1.4.5) researchers had identified the need for the incorporation of bank vegetation types into river regime (White, 1988) predictive models. As pointed out in 1.4.5, a need has arisen for a better classification of vegetation types with respect to bank protection attributes. This must incorporate not only the structural attributes of vegetation in terms of grasses, shrubs, herbs and trees but also aspects of ecological and physiological importance as discussed above.

Classification of vegetation as herbs, shrubs and trees in the context of their

values to bank stability may be questionable. For example, questions have been raised on the ambiguous nature of their value in terms of bank stability (De Ploey,1981). On a more applicable aspect, organisations such as the National Rivers Authority discourage the practice of growing tree species on the banks of rivers as they are obstructions to their dredging machines (Anglian Water: pers. comm.).

1.4.2 Water and Bank Vegetation - A geomorphological overview

Geomorphologists have been interested in the relationships between water flow and vegetation mainly in relation to soil erosion over the last few decades. For instance, Evans (1980) quotes Bennett (1939) on earliest quantification of the relative merits of good pasture (5% erosion) and woodlands (1% erosion) over bare soil. He further discusses the possible causes of reduction in erosion under varying degrees of percentage ground cover. In general, runoff and erosion increase rapidly in soils with less than 70% vegetation cover (Copeland,1965). Another important concept is that rates of infiltration of water through vegetated surfaces are high, thereby causing a reduction in runoff (Woodward,1943).

One has to appreciate this mode of empirical argument that Evans develops with respect to rainfall and land erosion accounting for a broad generalisation on percentage vegetation cover due both to the canopy and the litter. The crucial question is whether one could develop the empirical arguments for erosion in overland flow as Evans (1980) postulates, to the situation in a channel flow regime.

The motive force of water that causes dryland erosion is rain which falls mostly vertically as drops of varying size and momentum, on the leaves of the plants. But, in the case of a channel the motive force of lentic water acts laterally against the vegetation that protrudes up from the bank. It could well be said that as long as other motive forces, such as wind, do not irretrievably disorientate the canopy, the canopy itself will act as the 'buffer' to the impact of raindrops thereby preventing direct splash erosion.

Gregory (1992) discussing vegetation indicators of river channel adjustments identifies four possible causes of channel bank erosion. They are:

- (i) indications of vegetation free bank surfaces;
- (ii) exposed tree roots;
- (iii) undercut channel banks, and

(iv) trees growing at a low level in the channel causing undercutting.

Cooke and Doornkamp (1974) discuss the Universal Soil Loss Equation which is the basis of estimation of soil loss on land and hillslopes. Any attempt to relate this to the present study is considered unsuitable as some of the controlling factors considered in it are the rainfall factor, cropping and management factor and conservation practice which are not the priority topics quantified here. But their discussion on channel bank erosion presents the geomorphologists' aspects of interest. As they mention, the lateral motive force of lentic water in a channel poses a different situation from hill slope erosion. On a channel bank (as well as on a dryland slope) there is not only the gravitational force ($W \sin \theta$) exerted on each particle (where W is the weight of the particle) but also the lateral force generated by the motive force of the water. This force is proportional to τ_0 the shearing force on the channel bed. They point out that the critical shearing stress required to move a particle (τ_c) is related to τ_0 as

$$\tau_0 = \tau_c \times 0.75\gamma d s$$

where γ = specific weight of the fluid;

d = vertical depth of flow;

s = channel slope.

If it is either a sudden storm flow or flash flood as at initial stages of a monsoonal rain in the tropics or due to a sudden opening of an irrigation channel sluice gate, then the laminar flow that moves through the vegetation as well as its velocity will dictate the magnitude of the momentum of the motive energy. The total resistive force will be that of the vegetation and the soil of the bank. As such modified or novel empirical arguments have to be developed for bank erosion under different flow regimes. In fact, Morgan (1980) expounds that most faults observed in application of these theories to overland flow are mainly due to the theories themselves being derived from those developed for channel flow. Hence, it may be worthwhile to review the findings of hydrologists.

1.4.3 Water and Bank Vegetation - A Hydrological Overview

Over the last two centuries hydrologists have studied the flow through dense vegetation and simulated vegetal material. As the literature is quite considerable the reader

is referred to Judy (1987) who presents a comprehensive bibliography. The main obstacle to such studies has been the complex nature of the vegetation and the difficulty in defining quantifiable parameters which would be necessary for theoretical definitions and predictive formulations. All three widely accepted predictive models (see 1.4.3b) are based on allocated roughness coefficients as opposed to precisely measurable values. For the purpose of this thesis and the nature of the research carried out, it is considered best to summarise the general approach by hydrologists, their aspirations and achievements with appropriate criticism. The thrust of the critical analysis and argument is directed at identifying which inherent factors of a bank vegetation play a key role in preventing erosion. For example, are root systems more important than shoot systems? Is roughness factor (see 1.4.3b) the critical aspect to be included in predictive equations.

1.4.3a The 'problem' of bank vegetation in hydraulics

The fundamental question as to why hydrologists took vegetation into account is important. It was an impediment to:

- (a) the flow;
- (b) prediction of flow;
- (c) long-term flow control.

Judy (1987) accepts that vegetation protects the soil surface from erosion, by lowering the velocity of flow near the bed and it is an economic and efficient channel liner. He further states that even with rigid linings such as concrete and bricks, silting up does occur with time encouraging growth of vegetation. Yet his treatise is based on the concept that vegetation is a 'disruptive force' that prevents adequate channel design and operation. This is true if the final aim is to develop accurate predictive models of flow at the cost of ecological and socio-economic aspects. However, the hydrologists' overview of bank vegetation may have to be re-addressed to suit the twentieth century expectations of "eco-positive global environmental solutions".

Positive aspects such as the role of bank vegetation acting as a 'sink' (Jacobs and Gilliam, 1983) for fertilizer run off from farmland or that it may act as a filtering zone for inflowing physical pollutants overland in addition to bank stabilization are of importance. The first two aspects minimise pollution of the water while the third can be utilised as a

cheap but efficient channel liner which retains the channel geometry. It is appropriate to review hydraulic theories to assess the possible use of bank vegetation with a view to both bank protection and hydraulic predictions.

1.4.3b 'Roughness Factor' in theory and practice of predictive hydraulic formulation

Of the number of empirical predictive formulae developed over the last two centuries, the most accepted and used are:

$$\text{Chezy} \quad U = CR^{1/2} S_e^{1/2}$$

$$\text{Manning} \quad U = R^{2/3}/N S_e^{1/2}$$

$$\text{Darcy-Weisbach} \quad U = (8g R S_e / \lambda)^{1/2}$$

where U = mean velocity of flow

C = Chezy's roughness coefficient

N = Manning's roughness coefficient

λ = Darcy - Weisbach roughness coefficient

R = hydraulic radius

P = wetted perimeter

S_e = energy slope

g = acceleration due to gravity

The three roughness coefficients N , C and λ are related as follows (Judy, 1987):

$$C = R^{1/6} / N = (8g/\lambda)^{1/2}$$

As mentioned earlier in 1.4.3, a significant factor in predictive hydraulic modelling is that the roughness element is accounted for on an arbitrary scale. The immediate effect of introduction of a roughness element into an otherwise simple fluvial system is :

- i) the drag exerted on the vegetation, which increases the resistance to flow;
- ii) increase in shear force on the boundary, which decreases the mean velocity at the boundary.

Both these factors can be discussed in the light of the boundary layer theory of Prandtl von Karmen (Prandtl,1952) and Nikuradse (1933). This thesis does not encompass the measurement of these factors. But the importance of these theories are

taken into account with special significance to plant morphological characteristics in relation to both hydraulics and prevention of bank erosion.

As this investigation is based on emphasising the effects of bank vegetation on the hydraulic geometry of the fluvial system it is considered best at this stage to review :

i) some facts relevant to hydrologists on the variety of plants present within river corridors; This (1.4.4) may alleviate over-simplistic forms of classifications of vegetation, in relation to important composites of modelling, such as roughness coefficient and boundary shear stress. It may also add a new dimension to the arguments on such factors as the possible reasons for undercutting in banks with apparently dense vegetation or the need to identify the role of a group of plants which are adapted to survive in the basal region of a waterway thereby preventing any points of initiation of erosion which in turn may be the critical factor for the long-term dynamic equilibrium of the geometry of the channel.

ii) The River Regime theory (see 1.4.5), its development into the present day understanding of fluvial systems incorporating the role of bank vegetation, criteria for bank stability and the relationships for the state of dynamic equilibrium within an alluvial channel.

The argument that bank vegetation is a serious threat to flow efficiency of the channel is well discussed by Masterman and Thorne (1992). They argue that there has been an over-simplification and generalisation compounded by high roughness value (Manning's N) estimates being incorporated in the validation of flow models so far based on Manning's equation. They prefer the Darcy-Weisbach friction factor and argue that factors such as stiffness value of the bank vegetation have to be accounted for. This is based on the fact that herb species do flatten onto the bank with the floods thereby reducing the roughness height while increasing or optimising the effective hydraulic radius of the channel. They further argue that the effective height of the vegetation is further reduced during winter due to the loss of leaves.

1.4.4 Vegetation within the channel perimeter

Three categories of plants live within the perimeter:

i) Hydrophytes

These are plants that establish themselves in the main stream with their root systems well anchored to the bed. They are adapted to fluvial intensities of varying degrees as discussed in 1.4.1 above. Judy (1987) quotes that the effects of submerged vegetation on flow in ditches and canals of varying density and sizes may reduce the flow rate by as much as 97% from that predicted at the construction of the waterway. The coefficient of retardance, due to vegetation, as Manning's N (see 1.4.3b for Mannings equation) was 1.18. At low flow the massing together effect leads to a reduction in the cross section thereby leading to a flow retardance. The channel efficiency drops to 10%. But efficiency increases with higher flow rates that deflect the vegetation (Ramser, 1943). Vegetation may still cause flood damage by increasing the height of flood water.

In terms of relevance of hydrophytes to a study on bank erosion, the main effects will be on how they affect the flow of the channel. Therefore they are more appropriate for models on channel discharge. In fact, as Masterman and Thorne (1992) identify, one of main drawbacks of earlier models was the generalisation that the bed and the bank are treated as a single continuum.

ii) Semi-aquatic vegetation established in the basal region of the bank

For the purposes of this research, these are considered as the most important species of plants with reference to many factors of importance in bank stability. They are neither true hydrophytes nor are they true dryland plants. They are wetland plants of an amphibious nature with adaptive abilities to grow and survive if necessary either in dry or wet (aquatic) conditions. But their preferred habitat is semi-aquatic. The range of species is vast in the tropical countries but a significant number of species do exist in the temperate region. These plants have the following effects on the hydraulic system:

- a) act as a mediator between the bank and the main isovel; They reduce the shear stress imparted on the bank by the primary and secondary isovels.
- b) reduce the hydraulic radius of the channel and increase the velocity of flow;
- c) increase the roughness factor (see 1.4.3.b); Cook and Campbell (1939) observed that a flexible vegetation such as Sudan grass possesses a marked superiority over stiff stemmed species with respect to channel protection. Stiff vegetation was not flattened

with the flow as much as the flexible types. This is interesting from an evolutionary point of view i.e. survival of a plant species in relation to its realised niche by virtue of its adaptive architecture. For example compare the effect of two grass species, *Phalaris arundinacea* and *Agrostis stolonifera* var *palustris*. The former has stiff long stems while the latter is shorter thinner and more flexible. Both are wetland grasses but the latter may be preferred by a hydraulics engineer who seeks a better predictive flow. The former may be the choice of an ecologist for its potential as a habitat for a particular wetland fauna such as Mute Swans. Even from a purely geomorphic and hydraulic point of view Thorne et al (1988) conclude their discussion on prediction of hydraulic geometry of streams by accentuating the critical need for further research into this aspect of bank vegetation from a deeper understanding of plant biology.

d) may negate erosion at base (undercutting) as the semi-aquatic plant is invasive to a certain depth of water. Complications may arise as to the suitability of a given species for a particular fluvial system. For example, potential for initial establishment, survival under varying hydraulic intensities will govern the feasibility of introducing any such species in a given channel. If undercutting is a serious factor of instability of the bank geometry, then an understanding of the role of species such as *Phalaris arundinacea* is warranted. Such a study should test its ability to colonise the basal region of a channel bank. Special attributes in preventing or arresting the process of undercutting must be accounted for.

iii Bank vegetation of a non-aquatic nature

These are the vast range of plants that dominate the drier, upper areas of the banks (see 2.2.1f and Haslam,1978). They may vary from annuals to perennials, herbs or shrubs to trees. Haslam discusses this range of bank vegetation in considerable depth. This group of plants have been discussed in hydraulics literature from a different perspective. Its main attempt has been to identify an appropriate value coding (Ree and Crow,1977) based on either apparent plant density, ground cover or tree cover to enable the refinement of existing predictive equations for hydraulic flow. For the purposes of this study the following aspects of these plants are considered suitable :

a) non-uniform nature of the ground cover that exposes patches of bare soil which may be subject to erosion at different fluvial regimes;

- b) possible undercutting under certain vegetation in river banks which may present long-term problems of geomorphological and hydraulic significance; for example, bank slump under ambient flow or storm flow; Under ambient flow this may lead to debris accumulation at the base thereby affecting the flow, while under storm flow the debris may be carried away but the erosion may accelerate to beyond critical levels when the whole bank may be weakened enough to be destabilised totally.
- c) uncertainty as to any positive contribution (for example increase in soil cohesion) to soil slope stability by the presence of roots.

Quantifying root-soil cohesion may not be possible within the scope of this research program. However it may be an area of significant importance in identifying the role of vegetation in bank stability.

It may be worthwhile to observe how 'non-aquatic' bank vegetation responds to flood regimes. Two broad aspects are identified:

- (a) the morphological orientation , i.e. do they remain stiff or are there any signs to confirm the views of the 'effective height' school of thought (Kouwen, 1988)?
- (b) survival of the shoot and the root systems i.e. death and decay.

1.4.5 The Regime Theory

Blench (1986) defines a channel in regime as that which has acquired a long-term average steady state in boundaries of its transported sediment.

The river regime theory was developed by Lacey (1929,1930,1939, 1946) while working in the Indian sub-continent on an empirical basis where he related equilibrium dimensions and slope of canals to discharge and sediment load. These canals ran at near constant discharges and generally carried a sediment load of sand and silt. He introduced concepts and correction factors to the regime equations developed by Kennedy (1895) and Lindley (1919) by including the mean velocity, the hydraulic radius, the wetted perimeter, the flow cross-sectional area, the slope, the Manning's coefficient, and the discharge of a stable channel.

In his preface to the Proceedings of the International Conference on River Regime, White (1988) comments on two factors which would be considered of importance to this study :

a) while progress has so far been made on combining equations that describe sediment transport and alluvial friction, no approach to the problem of determining channel width has gained universal acceptance;

b) the radical approach of recent researchers with emphasis on the analytical or rational approach based on a theoretical description of the dominant fluvial processes is a 'quantum leap' from the purely empirical approach of Lacey et al.

Above all White expresses the need to develop a theory which relates the channel size and shape to the fundamental physical processes involved. He stresses the need to base the subject firmly on observations. Yet the difficulties that beset the scientist who seeks agreement between the calculated and the measured values are clearly explained by Thorne et al (1988) in their application of the Minimum Stream power Concept as discussed below.

i) The problem of determining channel width with particular emphasis on the role of bank vegetation in channel geometry

In the regime theory two sets of variables determine the long-term state of the system. They are :

1. the independant variables : (a) water; (b) sediment discharge; (c) bed and bank materials;
2. the dependant variables : (a) width; (b) depth; (c) channel slope;

Discharge which is highly variable through time is a continuity. To represent the effects of the range of flows experienced by the channel, the dominant discharge is selected.

The physical relations applicable to the analysis of hydraulic geometry are grouped into four categories: (i) fluid mechanics; (ii) sediment transport; (iii) bank stability; and (iv) dynamic equilibrium.

It is best that aspects of fluid mechanics and sediment transport be referred to in literature on standard fluvial hydraulics. The scientific literature on the topic is voluminous together with the academic arguments on modelling. The present study would be better served with an understanding of bank stability and the more topically relevant and exciting dynamic equilibrium.

ii) Bank Stability

The effects of bank vegetation with reference to prevention of bank erosion being

the main theme of this study, bank stability *per se* is a prime objective. However, bank stability itself depends primarily on the physical properties of the bank in both physical composition and geometry. White (1988) presents an insight into the development of bank stability theories, over the last century. In essence two categories of stability criteria can be developed. They are :

a) Physical aspects of bank stability intrinsic to the bank soil, which include:

- 1) soil physical properties such as bulk density and particle size;
- 2) angle of repose and the nature of the soil in terms of cohesion (broadly classified as cohesive, non-cohesive and composite banks);

b) Fluvial aspects of bank stability, which include:

- 1) fluvial forces of primary flow and boundary shear stress;
- 2) distribution of boundary shear stress;
- 3) secondary currents and boundary shear stress;

As this literature survey centralises bank vegetation as the intermediary between the fluvial forces and the bank soil (see 1.2.2 and 1.2.3) with bank stability as the tested criterion of efficiency of the bank vegetation the discussion will be limited to findings and opinions on the same theme by previous authors. Until recently, (Hooke, 1977), in Britain the need to quantify the relationship between fluvial aspects and bank stability incorporating bank vegetation was not suggested even though in North America, researchers such as Smith (1976) had quantified the effects of bank vegetation in terms of bank soil erodibility. Later authors such as Thorne (1978) developed ideas of incorporating the factor of vegetation such as grasses on the failure and erodibility of bank overhang.

It is clearly necessary to investigate the stability of a stream or river-bank in terms of its vegetation with special reference to two factors:

- a) the perpetually high moisture region (bank-toe) which is affected by the fluvial aspects mentioned above;
- b) the upper bank which is dry most of the year but subjected to fluvial stresses mostly seasonally (in winter).

Stability arising from the upper and lower regions of a channel bank is that which

leads to a dynamic equilibrium in channel regime.

iii) Dynamic Equilibrium in a channel in relation to bank vegetation

For an alluvial channel the state of dynamic equilibrium is governed by certain physical relationships. Chang (1980) adopts an analytical approach to dynamic equilibrium through the **Minimum Stream Power Concept** which states that "When the stream power per unit channel length, δQS , is a minimum subject to constraints, then the necessary and sufficient condition of equilibrium exists for a given alluvial channel. Water discharge (Q) and sediment load (Q_s) as independent variables tend to establish width, depth, and slope such that QS is a minimum". This is considered by Chang as the basis of analysis of hydraulic geometry.

The question is one of delineating acceptable predictive limits in using a theoretical hypothesis such as the minimum stream power concept. The test of such a hypothesis is in its validity in comparison with measured values. Such a test was carried out by Thorne et al (1988) for 62 sites on gravel bed streams of Great Britain. They compared the calculated values with the measured values of width, depth and velocity.

An error margin of plus or minus 15% was presumed as an acceptable level for design purposes of stable channels. But, for width alone, only 29 out of 62 sites (47%) fell into this range. Chang himself a co-author, noticed that the calculated widths tended to overestimate true values for small channels and underestimate width for large channels. As the bank material strength between sites was found to be very uniform, this parameter could not have a significant effect in causing the variation of hydraulic geometry.

However, it was noticed that bank vegetation varied between the sites. Therefore, Thorne et al decided to take account of the bank vegetation as a significant factor to be incorporated in the predictive models. They categorized the sites by the type and density of bank vegetation present.

Type 1	Grassy banks with no trees or shrubs; (weak)
Type 2	1 to 5% tree and shrub cover; (weak)
Type 3	5 to 50% tree and shrub cover; (strong)
Type 4	Greater than 50% tree and shrub cover, or incised into flood plain. (strong)

When they coded with the vegetation type the points in the graphs of calculated versus measured width and depth, a pattern emerged. Channels with weak bank

vegetation were generally wider and shallower, while those with strong bank vegetation tended to be narrower and deeper. They carried out a statistical analysis (chi square test) of calculated versus measured values and proved that the null hypothesis had to be rejected. Hence the conclusion was that the bank vegetation categories were significant and helped to explain the errors in the calculated widths, depths and velocities.

Then the regression curves for each of the bank vegetation categories were calculated separately. The r^2 values were significant at the 95% level of confidence, suggesting that more reliable hydraulic predictions can be made if account is taken of the bank vegetation on calculated width and depth measurements. Adjusted widths were within 15% of measured values in 77% of the cases from the previous value of 47% that did not take the bank vegetation into account. They predict that it should be possible to incorporate the effects of bank vegetation into analytical procedures by increasing the sophistication of the method of calculating the bank slope index. But the conclusion is that unless a considerable research effort is made there is no possibility of arriving at a simple relationship between bank vegetation, bank stability and channel geometry.

While the pioneering effort by Thorne et al (1988) in attempting to incorporate the bank vegetation as an important component in predictive models is praiseworthy, one has to be constructively critical about the approach adopted by them in the classification of 'vegetation types' in the above scientific analysis. Their basic idea of taking into account the 'type' and 'density' of bank vegetation is a relevant foundation. But the actual classification on types of vegetation is both too broad and elementary (grasses, shrubs and trees), and may not justify the use of the parameter of density of vegetation as much as a plant biologist may expect. On the matter of 'type' of vegetation the reader is referred to 1.4.1 above for some insight into the complexities of vegetation types.

Where density of vegetation is concerned a host of questions arise on the relevance of the classification adopted by the authors. For example, the density of vegetation may be appropriately defined as the number of unit plants per given area (Kershaw, 1980). On such a definition the most dense category is Type 1 (grasses). To consider grass as a weak vegetation type as stated by the authors may be an anomaly, especially in relation to fluvial hydraulics. This is because it may form a denser root

'mattress' in the soil. Such roots may enhance the shear strength of the top soil if Mohr's theory was true in the field situation. Alternatively it may not be reflected in the standard unit of measure of soil stability (shear strength). This is in fact one of the areas of study in this research project. Grasses may form a denser (more evergreen) foliage or 'phyllosphere' which would be more suitable to prevent surficial erosion by runoff. In winter the grasses would be more advantageous as the deciduous shrub and tree species will be of no appreciable value in terms of 'leaf area ratio' in botanical terms or 'ground cover' in its literal sense. It may well be that grassy vegetation may be categorised as a weak bank vegetation for bank stability when compared with tree species in discussions of regime theory concerning large rivers which develop extreme erosive potential at flood incidences. In fact prescribing grass as the stronger bank stabiliser than tree species on the banks of the Yellow River in China or the Brahmaputra in Bangladesh would be erroneous. On the contrary prescribing tree species on an irrigation canal bank as a stronger vegetation as a lining would be equally erroneous due to the ambivalent effects (De Ploey, 1981) such as increased stress arising from the weight of the tree.

These criticisms do not in any manner underestimate the academic value of the seminal paper on the incorporation of bank vegetation by Thorne et al (1988) in relation to identifying the potential value and possible improvements in Chang's concept. This recent acceptance by hydraulics researchers, for the necessity of the involvement of plant biologists and ecologists to improve existing hydraulic models, augers well for optimised future models. This study reach of the River Ouzel (see 2.2 and Plates 1 & 2) is more akin to a large irrigation channel than a main river. Therefore this study encompasses the effects on bank stability of grasses and herbs rather than of any tree species.

Recent research (Kouwen, 1988) identifies certain critical aspects such as stiffness of the vegetation. For example Kouwen measured a stiffness value of 153 Nm^{-2} for densely packed grasses with a height of 0.8m that reduced to 0.3m by deflection during floods. Yet there is considerable scope for improvements in the techniques for quantifying the stiffness values, as well as the necessity to identify the possibility of mixed species on the banks. Perhaps future priorities should lie in identifying reaches of a given channel with (say) more than 50% in density of a dominant species. Thereby stiffness values for

the bank vegetation for given reaches of the river may be facilitated to optimise the field performance of the model.

iv. The theoretical versus the empirical approach to modelling in fluvial hydraulics

There has been controversy on this topic for centuries on which approach is more suitable to a given situation. In fluvial systems such as in a well braided river with a vast number of variables which are dependent, independent or inter-dependent, the process of modelling on a theoretical basis is more complex than for a laboratory-based straight channel with a defined geometry. There are numerous variables to be accounted for. Hence the error margin is so great in predictive models as to be almost impractical in the field. This is reported in most agricultural irrigation schemes around the world. There are too many constants and coefficients in the regression models which attempt to explain the system in operation. More often than not the coefficients and constants themselves vary beyond reasonable limits to be of practical use. Diplas et al (1988) discuss the historical development of arguments and hypothesis on the meandering and braiding of rivers. They present a critical review of theoretical and empirical approaches to channel instability under varying hydraulic parameters. While there are three proposed hypothesis on the causes of river meandering (Chang, 1988), none of these consider the effects of uprooting or the absence of vegetation on the river bank as a possible cause of initiation of the meander. If 'basal end point control' (Thorne et al, 1988) is directly applicable to the process of undercutting of banks which in itself is a precedent to bank failure and the initiation of meandering, then it may be important to understand the process of basal end point control under the presence/absence of different types of fringe vegetation.

Empirical models may not take into account the whole range of diverse variable factors which lead to questions of validity of models of sound academic significance. The debate currently in controversy is that of pure science research in hydraulics and its applicability in the field environment. Vanoni (1984) for example sees the river engineer falling back from prediction to experience and intuition. Hey (1986) prefers to move forward to a fully rational river mechanics. Lewin et al (1988) are of the opinion that "geomorphologists contribute between these extremes erring to a state of 'quantified

intuition'!"

In a subject area of such inherent diversity and controversy both in the range of variables to be quantified and the accuracy of the models developed perhaps it is best to research with a lateral point of view. It is essentially one that would identify the possible components of the predictive model yet argues the paradox of the inappropriateness of the model being validated for a perfect predictive outcome. For example, the improvement by Thorne et al on Chang's minimum streampower concept by their own mode of categorization of bank vegetation may well have improved the predictive accuracy of the hydraulic geometry of channels by as much as 30%. Yet, there is another 23% to be accounted for. In addition their adopted mode of categorisation of vegetation would not satisfy a plant biologist. This brings in more complexity to predictive modelling. Such a lateral view may include factors such as the importance of considering adaptive architecture of bank vegetation, their stress tolerance as an evolutionary attribute and the value of research aimed not at the traditional mode of developing mathematical models but addressing questions of a more fundamental nature. For example a revision of the basis of classification of bank vegetation based more on species attributes in prevention of bank erosion than a general classification of herbs, shrubs and trees should be a prerequisite. Once the fundamental basis for a new approach to solving this age old problem of modelling hydraulic geometry for optimum predictions is proven to be worthwhile, then the next generation of researchers may draw on the expertise of the plant biologists and ecologists for more accurate predictions of bank geometry, stability and changes in channel morphology.

1.4. to 1.4.5. identified appropriate relationships between fluvial forces and bank vegetation within the perspectives of the three academic disciplines of plant ecology, geomorphology and hydraulics. The conclusion is that there is a necessity for identifying the role of bank vegetation in general (natural bank vegetation) and at least one species in particular (*P. arundinacea*, see 1.4.1) in terms of reference to the three disciplines :

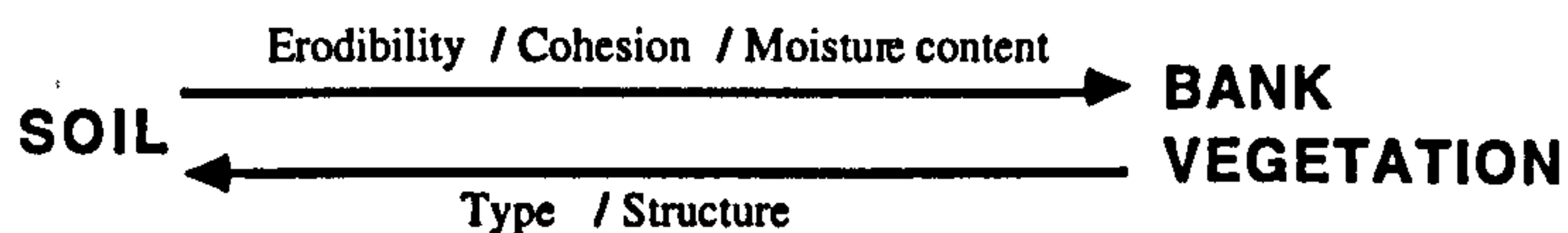
- 1) Civil engineering: shear strength variations in relation to rooting characteristics of plant species and bank soil stability as important in geomorphology;
- 2) Fluvial geomorphology: fluvial effects at different heights up the bank at different flow

regimes with respect to bank stability and erodibility;

3) Plant ecology: establishment of vegetation (*P. arundinacea* and natural re-vegetation) and its relevance to submergence stresses in aspects of short and long-term stability of the bank with the inherent ecological perspectives of adaptive strategies such as waterlogging and root survival;

These are more important aspects to be addressed at this stage prior to any attempt at predictive hydraulic modelling.

1.5 Relationship between Soil and Bank Vegetation



The main inter-relationships between soil and bank vegetation are dependent on the five subjective components shown above.

In essence, the research programme needs to identify whether there is sufficient reason to believe that bank vegetation has any effect on the erodibility, cohesion and moisture content of the bank soil. The effects of soil type and structure on bank vegetation will not be considered further in this thesis [see Haslam (1978) for a full discussion of the subject].

The dynamic stability of the soil-bank vegetation system is an example of an interdependant system arising out of a major non-living (physical) component and a living (biological) component. The paradoxical situation that arises is that even though the two main parameters have an inherent fundamental composite status in the system (see 1.2.3), it is the nature of the variations of the subjective components that will ultimately delineate the stability of the system. In conventional civil engineering techniques used to stabilise banks, there is no living component. Therefore the main substitute for bank vegetation (for example, a gabion or a metal bank revetment) can exert pre-defined stability to the hydraulic system.

Attempts to interpret or simulate natural raw material such as plants in stabilisation of soil differ between different academic disciplines. For example, civil engineers

simulate plant roots using synthetic fibres in their studies (Kassif and Kopelovitz, 1968) while soil scientists (Reid and Goss, 1981) take into consideration the more 'biologically important' aspects of root exudates in contributions to soil cohesion and express it in terms of soil aggregate stability rather than the quantification of shear strength in terms of a civil engineering model concept. The former concept limits itself within the definitions of conventional 'building blocks' for engineering practice while the latter encompasses the wider concept of 'living and changeable' building blocks. The latter view inherently carries with it the strategies which plants can adopt under varying conditions which is a missing factor with the analogy of synthetic fibres.

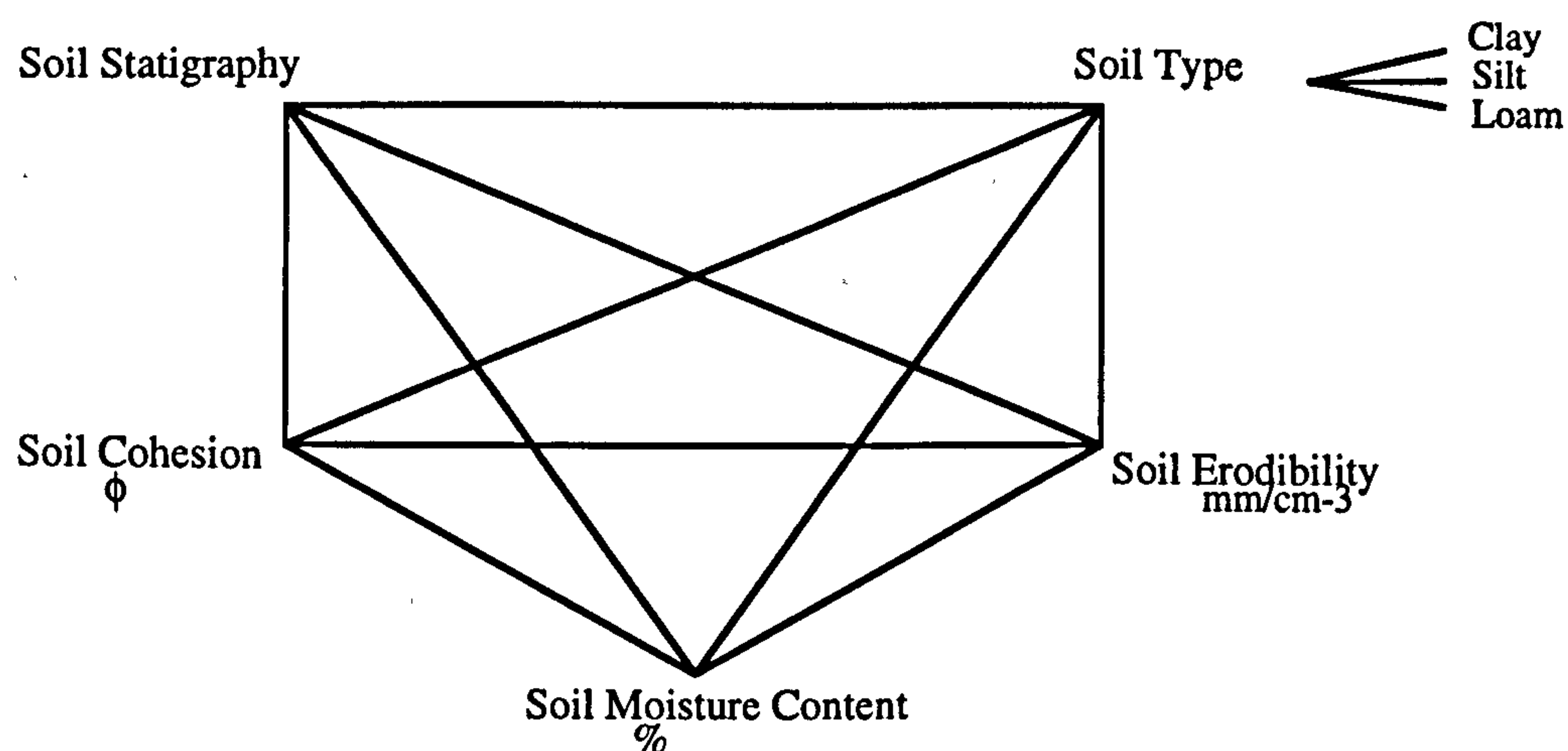


Fig1.2 Main Physical Components of the soil in relation to erosion

1.5.1 Cohesion

Rosenak (1963), discussing the shear strength of a soil delineates (a) friction and (b) cohesion, as the basic components of importance. These form the main parameters in Coulombs Law (see 2.3.3). He expresses cohesion as " a term which is influenced by the grain size, the state of packing of the soil particles and the water content ". The reason for the cohesion of clay particles to one another has been revealed by physio-chemical studies (van Olpen, 1963). For bare (non-rooted) soils the cohesive strength arising out of bonding between particles depends on the balanace between electrostatic forces of repulsion and van de Waals forces of attraction.

Bank vegetation imposes the aspects of establishment of roots, and water relationships which in turn affect the cohesion of the soil particles. A highly cohesive soil such as clay offers a good base for root anchorage whereas a non-cohesive sandy soil

offers a cutting surface which induces root growth but does not offer such advantages in anchorage or retention of water for physiological activities.

On the other hand, as mentioned above, the root exudates from the bank vegetation may increase the cohesive properties of the soil particles (Reid and Goss, 1980, 1981) and be termed as a causative factor in increased 'soil aggregate stability'.

For the purposes of this study neither the friction angle nor the cohesion of the soil is to be quantified. Only the shear strength of the soil, which inherently incorporates both factors, will be quantified. The nature of this study (i.e. the questions of whether bank vegetation has a relationship with (a) soil shear strength, and (b) soil erodibility or both ?) demands evidence of a more fundamental nature. If there is a positive relationship between shear strength values and root density then the discussion should be more based on similar findings for laboratory and dry slope studies by other authors. If however there is no such relationship for the first question (i.e. does vegetation increase shear strength of the bank?) but there is a positive correlation for the second question (i.e. does bank vegetation prevent soil eroding?) then there is sufficient reason to believe that the shoot system may act as a physical barrier.

1.5.2 Erodibility

Literature on effects of vegetation on soil erodibility discuss erodibility of bare soil and under vegetation (Altschaeffl and Christensen, 1965; ASCE Task force Committee, 1968; Morgan, 1986). In this study the comparisons are to be made on the basis of spatial (bank-toe versus the upper dry bank) and temporal (including seasonal and non-seasonal changes of the hydrograph) aspects.

As discussed with reference to cohesion (see 1.5.1) conclusions will have to be based on whether shear strength is related to erodibility of the soil. If there is no such relationship then the possibility of other factors associated with either roots or the shoots may have account for non-erodibility.

The first question is whether any other effects of roots (apart from shear strength) may influence soil cohesion. (Reid and Goss, 1980) attributed the increase of 'soil aggregate stability' under perennial rye grass to the release of organic substances from the roots. This view is in keeping with the electron micrographs of Campbell and Rovira

(1973) which showed the covering of soil particles with mucilagenous materials of plant, microbial and mixed origins. Organic materials released by living roots into soil may amount to 40-79% of the harvested root dry weight (Barber and Martin, 1976; Martin, 1977). Mucilage constitutes a further appreciable fraction of the total material released by plant roots (Samtsevich, 1965; Barber and Martin, 1976). Oades (1978) suggests that the above in addition to the mucilages produced by rhizosphere micro-organisms are probably predominantly polysaccharides that are potential stabilizing agents. There is however a lack of explanation in identifying a link between soil erodibility and soil shear strength through the above studies.

The critical factor for all these propositions to prevail in the rhizosphere is that the roots should be alive. In the present study it is proposed to de-vegetate the banks using a systemic herbicide. This should ensure that the roots are dead within a short period of time. What is observed then should reflect the state of the soil due to the loss of the live roots. In effect the first few months of the experiments (see 3.5.2 to 3.5.4) should indicate whether live root effects (factors such as any contributions to root-soil cohesion by mucilages or tensile properties of the roots) should be reflected in increased bank erosion and/or loss of shear strength.

Another question that arises is the definition of uprooting of seedlings, plants and breakage of plant parts by the motive force of the water. Haslam (1978) quantified the erodibility (= uprooting) of different species of plants under varying hydraulic regimes. The conclusions are that different species of plants withstand erosion both *en masse*, and as erodible parts such as branches or seed pods, at various hydraulic discharges. These are dependant on the motive force of the water and the soil composition. The ability of different species of plants to withstand different hydraulic regimes is considered to be linked to their evolutionary attributes with regard to survival of the individual and the mode of reproduction. But this will not be quantified in this study.

The main feasible alternatives to root effects on soil erodibility are the shoot effects. If roots have no effects on soil erodibility, then shoots may explain less erodibility under vegetation. Perhaps root effects are limited to anchorage of the plant while shoots have profound effects.

Where general methods of erosion measurement are concerned, Lawler (1991) identifies three disadvantages in current erosion measurement methodology. They are: (i) underestimation of the dynamism of the contemporary landscape; (ii) imposition of great uncertainty on process inference and hypothesis discrimination; and (iii) permit only limited verification of erosion models of high temporal resolution. His concern on the dynamic nature of a site in terms of erosion and deposition as two sequential processes dependent on the forces acting on the site acting at any given time were foreseen in this study (see 2.4.1 and Fig. 2.9.).

1.5.3 Moisture Content

The importance of moisture content as a critical factor in bank erosion was qualitatively described by Wolman (1959). A more detailed study of both precipitation and the relative importance of high moisture contents on the erodibility of different types of banks was carried out by Hooke (1977). She confirmed that bank soil moisture content is a prime factor that accounted for high erosion on certain river banks. High flows and high moisture levels on the banks were linked to the processes of corrosion and slumping respectively (Hooke, 1979).

In terms of bank erosion most studies carried out so far have dealt with actively eroding river banks. On the contrary, field observations clearly showed that under vegetated and apparently stable banks which did not have a presence of semi-aquatic fringe plants in the toe-region, there was evidence of undercutting at the bank-toe level which coincided with the ambient flow levels of the river. It so happens that for most of the year this is the region of the bank which is subjected to both factors that Hooke found as the key factors for bank erosion (i.e. fluvial motion for corrosion and high moisture content for slumping). The main differences between what occurs as an on-going process through ambient flow (normally summer in the temperate countries and non-monsoonal in the tropical countries) and the storm flows (normally winter in temperate and monsoonal in tropical) are in the magnitude of the flow and its effect on the spatial aspects of the whole bank. If the process of bank erosion is one of a pseudo-cyclic nature of : undercutting > wet-bank slumping > fluvial entrainment of slumped material > undercutting (Knighton, 1984), then as much as this process occurs at the mega-scale at

high flows, there is the possibility of the same process occurring at the meso-scale at ambient flows. Unless the toe-region consists of highly cohesive (clayey) material then such an on-going process will weaken the upper bank with time or create positions of local bank instability/erodibility. Therefore one aspect of this study as mentioned in 1.3, 1.4.3 and 1.4.5 will be to understand this phenomenon if it exists.

The other important aspect relating to moisture content of vegetated banks concerns the shear strength of the banks. It would be difficult to accommodate a study of evapo-transpiration by vegetation which may indicate a critical role of the bank vegetation (Waldron and Dakessian, 1982) with reference to moisture content of the banks. In order to identify any patterns of variation of moisture content under different vegetation and their effects on the shear strength of the banks both parameters will be quantified.

1.5.4 Soil Type and Stratigraphy

Both subjects have been dealt with by many authors with relevance to their research interests. In fluvial geomorphology soil physical composition and stratigraphy play critical roles in soil erodibility and channel geometry (Knighton, 1984). The structure of the bank and its constituent material determine the mechanism of bank failure (Thorne, 1978). Banks may be classified as being non-cohesive, cohesive or composite in structure. A non-cohesive bank is inherently prone to high erosion at low fluvial forces due to the high sand, gravel and cobble content. A cohesive bank on the contrary has a high silty clay composition. Alluvial banks formed on a meandering river on a floodplain are mostly composite banks (Turnbull et al, 1966). In composite banks with a non-cohesive sand and gravel overlain by cohesive sandy silt, the process of fluvial under-cutting poses a major problem. Continuous bank erosion by under-cutting leading to overhang cantilever formation which in turn fails due to shear, beam or tensile failure (Thorne and Lewin, 1979). The same authors identify natural re-vegetation as an important process in arresting this process. In terms of vegetation and bank soil types the prime factor of importance is in the ability of different species of plants to establish themselves on the given soil. Haslam (1978) discusses this at length.

This research study is carried out in one stretch of a local river (see 2.2.) with the idea of testing new hypotheses (see 1.6). This inevitably reduces the necessity of an

extensive study of soil type and stratigraphy to account for any variability within the data of the main experiments. However site characteristics in the form of a detailed soil physical analysis has been carried out (see 2.2.d).

1.6 Summary of the Research Proposal

Prior to defining the hypotheses to be tested in this study it is appropriate to summarise the sequence of events and reasons for formulation of the hypotheses. The original idea of addressing effects of bank vegetation on channel bank erosion arose on the basis of:

- i. field observations on the traditional use of bank vegetation globally, as a means of prevention and alleviation of channel bank erosion; however it was obvious that major international consultants were reluctant to use such "non-structural techniques"; The reason for this was the absence of a "scientific understanding" as to how vegetation could substitute for standard scientifically explainable "structural techniques" (Kraatz (1977).
- ii. research observations of the author (Ridge and Amarasinghe, 1984; Ridge, 1984) that certain species of plants varied in their morphological response to submergence; while such research was oriented towards an understanding of the physiological aspects, the observations on the morphological responses of experimental plants under flooded conditions sparked off a hypothesis of a different nature; for example, it was considered worthwhile to test whether plants had survival strategies not only for themselves but also conservation of their habitat; the underlying argument would be "*if plants did not incorporate such a strategy, then their survival is not guaranteed due to erosion of their habitat*"; the literature survey (cf Haslam, 1978) confirmed this view;
- iii. need to quantify the effects of bank vegetation as an effective bank liner in preventing erosion of the banks; this would fill a gap in the scientific verification of an otherwise "traditional and descriptive" understanding of the effects of bank vegetation; ideally, civil engineering terminology and techniques (eg. shear strength of the soil, shear vane measurements) should be used in the quantification; this would facilitate a direct comparison with "structural techniques" used in civil engineering; ideally such quantifications should be easily incorporated into existing classical scientific models such as the Darcy-Weisbach or Mohr Coulomb equations;

The next step was to attempt the development of a scientific model, preferably as a development from an existing model, so that it can be tested through the experiments and the survey. The literature survey encompassed past research and models on soil erosion by water and in turn under vegetation. Two schools of models are identified:

1. hydraulic models where vegetation is accounted for as an expression of the roughness characteristics (see 1.4.3); from a plant biological perspective this is essentially the incorporation of a phyllospheric effect (as opposed to the rhizospheric effects);

The reasons for the failure in predictive capability under varying field conditions are identified. The need to optimise such a model through a deeper understanding of plant biology is recommended.

2. geomorphological models where effects of vegetation on soil erosion are based on root effects (see 2.3.3); this model is based on the shear strength characteristics of a soil in relation to factors such as soil cohesion; the hypothesis proposes (cf Waldron and Dakessian, 1982; Gray and Leiser, 1982) that increased soil cohesion is contributed by increased root density and hence soil stability;

The dilemma from a plant biological perspective is that a plant is a unit composite of the root system as well as the shoot system. The two components are intrinsically linked in form and function. For example, the summer foliage and hence the roughness value (Manning's N) will be severely reduced for the dead flattened skeletal vegetation during the winter period. This fact has been identified and researched on later by other authors (see Masterman and Thorne, 1992). The root system, on the other hand, may be more proliferating in autumn and winter. Under such circumstances the Darcy Weisbach or the Mohr-Coulomb models have to account for drastic and regular seasonal variations. Apart from the above, questions may be raised on how holistic the research is if only either the root system or the shoot system alone is presumed as effective in negating bank erosion.

The literature survey proved the futility complexity and enormity of developing a universally applicable holistic model on predictive channel bank stability. This fact is later discussed in depth by Chadwick and Morfett (1992) under "morphological computational river modelling". They identify historical attempts and the present situation under the fifth

generation of models which have the facilities of computer aided design (CAD) , geographic information systems (GIS) and artificial intelligence, yet fail to produce an optimal predictive model for the problem. Under such circumstances, the alternative is that of an experimental approach of a "scientific explanation" to that of falsification of a testable model, as recommended by Boardman et al (1990).

In contrast to the dependance of quantifying bank erosion under the premise of root effects (Smith, 1976) a more holistic approach is identified. Such a view is derived from observations of Hooke (1977a, p.336) viz. *"the floods may have initiated erosion by removing vegetation and attacking stable banks"*. A need to address the effects of vegetation as a whole is identified.

Ideally the research programme should address shoot effects as well as root effects. The final analysis may identify a need to prioritise whether it is the root system or the root system (or both) that play/s a critical role in terms of effects of bank vegetation on channel bank stability. On the basis of the above reasoning, the following hypotheses were tested.

Hypotheses tested in the study

- 1.a** increases in root density are reflected in higher shear strength of the soil;
(see 3.4.4.; 4.5 and Ch. 6);
- 1.b** high shear strength of the soil is indicative of less erodibility of the soil;
(see 3.4.3 and 4.5.1);
- 2.** the shoot system is associated with reduced bank erodibility; it acts as a physical barrier between the motive fluvial forces and the resistive bank soil;
(see 3.4.2; 4.4 and 5.4);

In addition, the following question is asked:

- i.** is secondary succession (natural re-vegetation) an effective and essential contributor to self-balancing of a natural fluvial ecosystem?

This is addressed in Experiment 3 (Ch. 5).

Chapter Two

Methodology

2.1 Rationale of experiments and survey

The literature survey in Chapter 1 was concluded with the outline of the topics for further research (see 1.6). While much work has been done on fluvial erosion in the banks of straight channels and bends of streams and rivers in positions bare of vegetation, with erosive processes already in progress (Wolman,1959; Knighton,1973; Hooke,1977; Thorne,1978; Guy,1981), not so much literature is available on the the process of initiation of erosion or the underlying mechanism of intiation of both corrasion and slumping. This necessitated an experiment that compared a freshly denuded area with a naturally vegetated area of the same waterway. In such an experiment, it was necessary that the two factors be compared under conditions where parameters of hydraulics, soil properties and site characteristics were identical, as far as possible.

Thus, the *first experiment* was a comparison of soil erosion between vegetated banks versus non/de-vegetated banks. The other experiments were to delve deeper into the effects of types of vegetation on erosion in natural waterways and the effects of revegetation both naturally and artificially. The parameters quantified are identified as follows:

- a) Shear Strength of the soil (1.5.1);
- b) Moisture content of the soil (1.5.3);
- c) Root density of the bank vegetation (1.4.4);
- d) Erodibility of the soil (1.5.2);

While most previous research has been done on the effects of different species of grasses (Whitehead,1976) on both bank erosion and changes of hydraulic characteristics, hardly any work has identified the complexities brought about by the morphological diversity of the plant species. As such an attempt is made at identifying any variations in bank erosion under natural vegetation other than grasses.

This study incorporates measurements of erosion at the toe region of the bank to investigate any aspects of cumulative erosion at ambient flow. The significance of this is to ascertain clues to possible differences in rates of erosion under vegetated banks and non-vegetated banks.

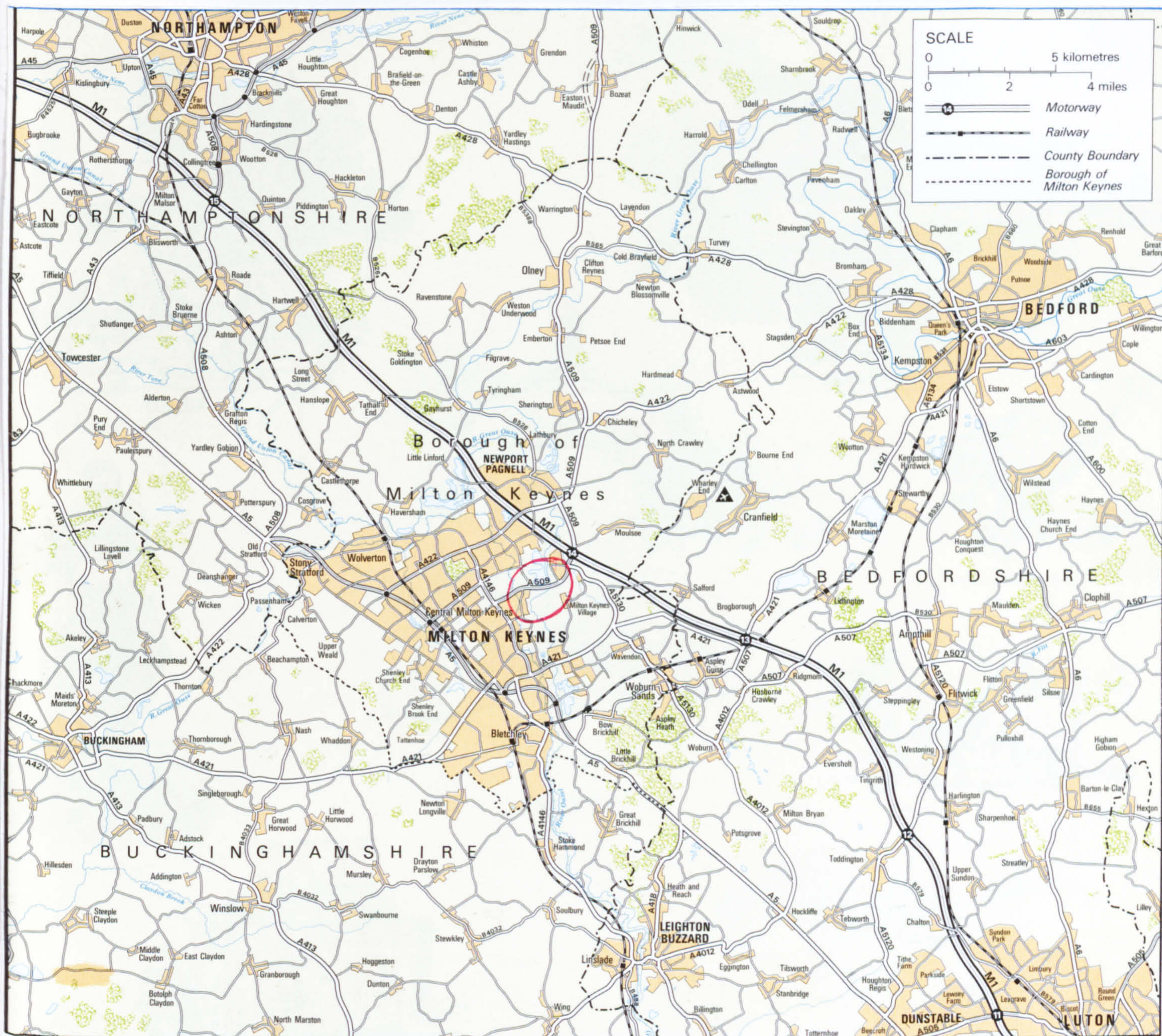
Root structural diversity might be expected to affect the shear strength and the root area ratio of the soil in such a manner as to be a critical factor in the processes of initiation, establishment and perhaps in the cessation of fluvial erosion. Hence the *second experiment* was to study the effects of artificial establishment of a wetland grass monoculture on fluvial erosion. The grass chosen was *Phalaris arundinacea* L. (Reed canary grass) which is a well known coloniser of river and lake banks and has a dense mat of roots and rhizomes (Marten,1985; Grime et al.,1986).The establishment of this grass within two years both in density and position on the bank were considered to be of interest.

Previous experiments on the effects of grasses on erosion were conducted either in the laboratory or the field under ephemeral conditions. Under natural field conditions plant succession on a bank subjected to seasonally varying hydraulic conditions may present problems, in validation of conceptual model. These problems may range from variations in plant density (Kays and Harper,1974), to possible changes in bank soil properties brought about by variations of organic matter content depending on the species present.

Notable within the scientific literature on primary or secondary succession of vegetation on banks of waterways, Haslam (1978) indicates the diversity of species established at varying heights of banks of waterways with various soil properties and hydraulic conditions. As grasses have been the subject of scientific investigations on canal linings so far, it was decided to choose a wetland type of grass (*Phalaris arundinacea*) that grows naturally on river banks. It has the ability to grow under varying soil moisture regimes and has an extensive underground system of roots and rhizomes.

The *third experiment* was to observe the process of natural revegetation on a river bank that was subjected to a season of denudation and erosion. While bank vegetation is regarded as useful in preventing erosion (Smith,1976; Kouwen and Li,1980), and is aesthetically valuable, there is a paucity of literature quantifying and correlating changes in both vegetation and soil properties during secondary succession after erosion by an extreme occurrence such as herbicide denudation.

This experiment was intended to study the changes of plant species and soil characters of the bank profile during secondary succession after denudation by a herbicide.



Based upon the Ordnance Survey Map with the permission of the Controller of H.M. Stationery Office. Crown Copyright Reserved

Fig. 2.1 Map of Location of Experimental Site

2.2. Experimental Layout

As discussed in 2.1. above three main long-term experiments were carried out. The option of carrying out these experiments at different locations on different rivers or in different locations of the same river was ruled out due to the following reasons:

- i.** it would replicate the identification and quantification of site characteristics, soil properties and hydraulic data;
- ii.** difficult to find another straight stretch of the river in the Milton Keynes area;
- iii.** it would be more relevant to carry out the experiments in the same uniform stretch of the river. In essence, this is similar to the situation of many experiments being carried out in a single laboratory. The assumption is that all extraneous factors such as temperature, wind, drainage, flow regimes, rainfall etc. are kept as constant as possible for all the experiments. Most deviations in the findings of similar experiments by two or more scientists working in various geographic locations are usually attributed to contrasting locations. The results and inferences from each experiment would be valuable. An attempt to relate the data of several experiments in a permutational manner may be even better. The validity of such an attempt is guided by the constancy of the extraneous factors mentioned.

The size of each plot and the number of replicates were such that one person could manage to carry out the field work. The initial plot size chosen was 5m x 5m. As the bank apex was 3m from the toe-region the effective area of study per plot was 5m X 4m. This minimised any soil disturbance caused by regular sampling for the quantified parameters (erosion, shear strength, and root density). This plot size was a reasonable one in which a significant number of samples for each plot could be gathered as a representative quantity. Each treatment had six replicates. As such the number of plots for each experiment was twelve.



Plate 1. Experimental site in September 1986 (view up-river)
N.B. de-vegetated plots on the banks



Plate 2. Experimental site in August 1988 (view up-river)
N.B. Plots 2a & 2b with *P. arundinacea* in flower on either bank

2.2.1 Description of experimental site

(a) Position and General physical characteristics

The experimental site chosen, is on the river Ouzel (see Plates 1 & 2), flowing through Little Woolstone (National Ordnance Survey Grid Reference: SP 877 393) in Milton Keynes, in Buckinghamshire. As shown in the map (see Fig.2.1; map) the river flows in a north-easterly direction at this site over a distance of 800 metres approximately. On the eastern bank of the river there is adjacent farmland which is not subjected to much human or animal trampling pressure. The western bank has a public footpath running parallel to it approximately fifteen metres from the river. Beyond this is the main Woolstone park which is flat land, with a plantation of Poplars, mainly *Populus tremula*, Silver Birch (*Betula pendula*), and lime, mainly *Tilia cordata*. None of the trees was closer than forty metres from the experimental area. This avoided any possible complications arising from the effects of tree roots or canopies being too close to the banks. The surrounding land is flat with no significant variations in topography (see Plate 1)

(b) History of the bank

This stretch of the river was channelised around twenty years ago as part of the Milton Keynes development programme which included a system of balancing lakes that were inter-connected via the river Ouzel (personal communication: Milton Keynes Development Corporation and Anglian Water Authority). As such the vegetation on the banks comprises naturally colonised species. A comparison with the older stretches of the river banks indicates that the bank vegetation on the experimental site is similar.

(c) Soil properties of the bank

Two main properties of the bank soil were studied. The positions of measurement were at approximately 0.75 m and 1.75m from the toe-region at the edge of plots 1a, 1b, 8a, 8b, 15a and 15b. This encompassed the edges and the mid-region of both banks of the length of river studied.

i) Soil particle size analysis (Archer and Marks, 1985): The top 0 -15cm layer of soil was cored using a 5cm internal diameter soil augur. These were subjected to analysis at the Silsoe College laboratories. Samples were taken from plots 1a, 1b, 8a, 8b, 15a and 15b at

0.8m and 1.75m upwards from the bank-toe. Results are shown in Appendix 9. The soil was sandy clay on average (sand 60 -70%; clay 25 -30% and silt 8 -15%).

ii) **Soil Bulk Density** (Archer and Marks,1985): Bulk density was measured at the 0 -10cm depth. Samples were taken from plots 1a, 1b, 8a, 8b, 15a and 15b at 0.8m and 1.75m upwards from the bank-toe. Results are shown in Appendix 9. An average of 1.002 +/- 0.012 g cm⁻³ was observed. The low values are attributed to the effect of death of roots (due to systemic herbicide application) thereby leaving a highly porous soil, in the Bare banks and plant debris accumulation in the soil under long established vegetation in the Natural Vegetation plots.

(d) **Hydraulic details of the site** (see: Appendix 1); The original slope of the bank at construction was 1.5 : 1.

(e) **Description of bank vegetation** The list of observed plant species is typical for lowland British streambanks. The following were present among and adjacent to the main natural plant cover which consisted mainly of *Urtica dioica* and *Epilobium hirsutum* in the mid-bank region with grasses at the apex of the bank.

(f) **Species of plants on the banks of the experimental area of the River Ouzel**
(surveyed on 6th August 1987)

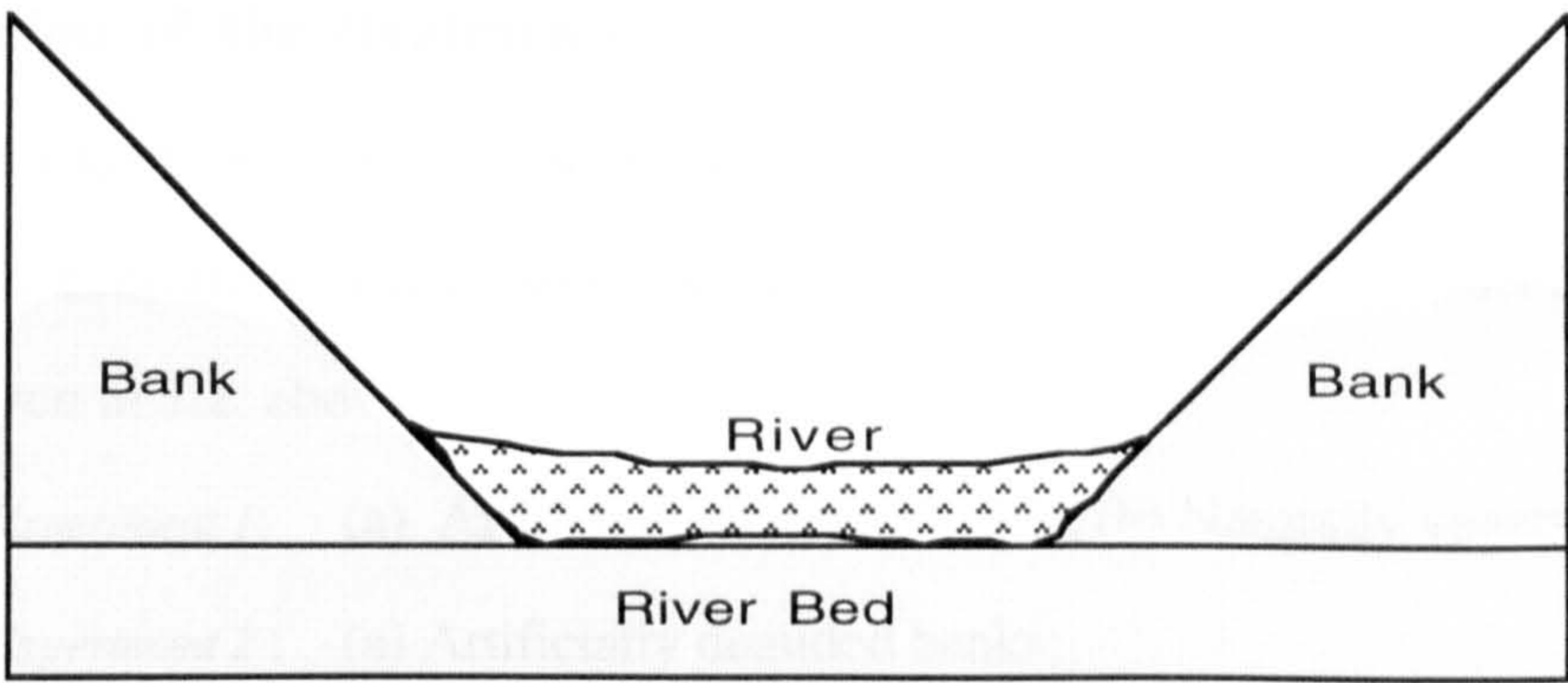
<i>Alopecurus geniculatus</i> L.	Marsh foxtail
<i>Agrostis stolonifera</i> L.	Creeping Bent
<i>Agrostis capillaris</i> L.	Common Bent
<i>Agrostis canina</i> L.	Velvet Bent
<i>Arrhenatherum elatius</i> (L.) J.& C.Presl.	False Oat grass
<i>Conium maculatum</i> L.	Hemlock
<i>Cirsium arvense</i> (L.) Scop.	Creeping Thistle
<i>Crepis capillaris</i> (L.) Wallr.	Smooth Hawk's-beard
<i>Crepis biennis</i> L.	Greater Hawk's-beard
<i>Dactylis glomerata</i> L.	Cocksfoot
<i>Dipsacus fullonum</i> L.	Common Teasel

<i>Festuca rubra</i> L.	Sheep's Fescue
<i>Festuca arundinacea</i> Schreb.	Tall Fescue
<i>Galium aparine</i> L.	Goose Grass
<i>Geranium pratense</i> L.	Meadow Cranesbill
<i>Geranium robertianum</i> L.	Herb Robert
<i>Glyceria maxima</i> (Hartm.) Holmberg.	Reed Sweet Grass
<i>Heracleum sphondylium</i> L.	Hogweed
<i>Holcus lanatus</i> L.	Yorkshire fog
<i>Impatiens glandulifera</i> Royle.	Indian Balsam
<i>Lolium perenne</i> L.	Rye grass
<i>Myosoton aquaticum</i> (L.) Moench.	Water Chickweed
<i>Papaver rhoeas</i> L.	Common Red Poppy
<i>Phleum pratense</i> L.	Timothy Grass
<i>Polygonum amphibium</i> L.	Amphibious Persicaria
<i>Poa annua</i> L.	Annual Meadow grass
<i>Poa palustris</i> L.	Marsh Meadow Grass
<i>Poa pratensis</i> L.	Meadow Grass
<i>Rumex acetosa</i> L.	Common Sorrel
<i>Rumex acetosella</i> L.	Sheep's Sorrel
<i>Rumex conglomeratus</i> Murr.	Sharp dock
<i>Rumex hydrolapathum</i> Huds.	Great Water Dock
<i>Solanum dulcamara</i> L.	Woody Nightshade
<i>Solanum nigrum</i> L.	Black Nightshade
<i>Stachys palustris</i> L.	Marsh Woundwort
<i>Silybum marianum</i> (L.) Gaertn	Milk thistle
<i>Sisymbrium officinale</i> (L.) Scop.	Hedge Mustard
<i>Taraxacum officinale</i> Weber.	Dandelion
<i>Trifolium dubium</i> Sibth.	Lesser Yellow Trefoil

2.2.2 Design of experimental layout

One could develop a simplified pictorial geometrical model of this reach of the river (see Fig.2.2). Fundamentally, it consists of two symmetrical longitudinal prisms of soil overlying a saturated horizontal, longitudinal rectangle of soil. The distinction between a study of bank erosion as opposed to bed erosion overlies the above mode of geometrical presentation.

To identify the causes and extent of erosion up the bank an area of 4 - 5m up from the base of the river bank was chosen. Having delineated the size of the plot (see 2.2.for further reasons), and taking into consideration the length of the straight stretch of the river that could be used, the number of replicates of a treatment per experiment was assigned. The straight channel of the river afforded the advantage of using both banks for similar allocation of treatment plots on either side of the river for all three experiments (see Fig.2.3).



Fig,2.2 : Simplified Geometrical Model of a Cross Section of the river

Such an allocation of the plots nullified the possible effects of variations of the erosive or sedimentation effects of one plot directly affecting the adjacent or opposite plots. It has been observed that once initiation of erosion at one point of a bank occurs there forms a differential effect between the primary isovels and the secondary currents on immediately opposite banks (Thorne,1978). The result is changes in hydraulic flow along the transect area thereby leading to the formation of meanders and ox-bows with time. Allocation of the same treatment as opposite pairs would tend to negate such effects. In addition it was appropriate to allow a margin of natural intact bank between adjacent plots. This precaution would further negate or buffer the carry over effect from one treatment over to the adjacent plot. It would also allow the field worker to have access to and from the river at any plot without having to trample on the experimental plots. As the total length of the straight

stretch of the river available for experimentation was over 500 metres (of which only $5 \times 15 = 75\text{m}$ were needed for the actual plots per bank) it was decided that this inter-plot margin could be three metres in width.

The next step was the allocation of treatments for the experiments that were carried out. Three major long term experiments were proposed as discussed in 2.1. earlier. The total number of plots marked out in May 1986 for the initial experiments was thirty. As they were oppositely paired per treatment, the final step was one of deciding the best allocation of plots per experiment. For statistical reasons and to allow for random variations in soil, vegetation and river characteristics, paired plots were allocated at random along the bank using a table of random digits. The plots along the banks were numbered from 1a to 15a and 1b to 15b on either side, the river flowing from the South-East to the North-West. Figure 2.3 shows the arrangement.

2.2.3 Description of the treatments

All three experiments involved comparisons of erosion of the river banks under varying hydraulic conditions. The reasons for carrying out all three experiments in the same locality were given in 2.2. above.

Treatments for *Experiment 1*: (a) Artificially denuded banks; (b) Naturally vegetated banks;

Treatments for *Experiment 2* : (a) Artificially denuded banks;
(b) Artificially re-vegetated banks;

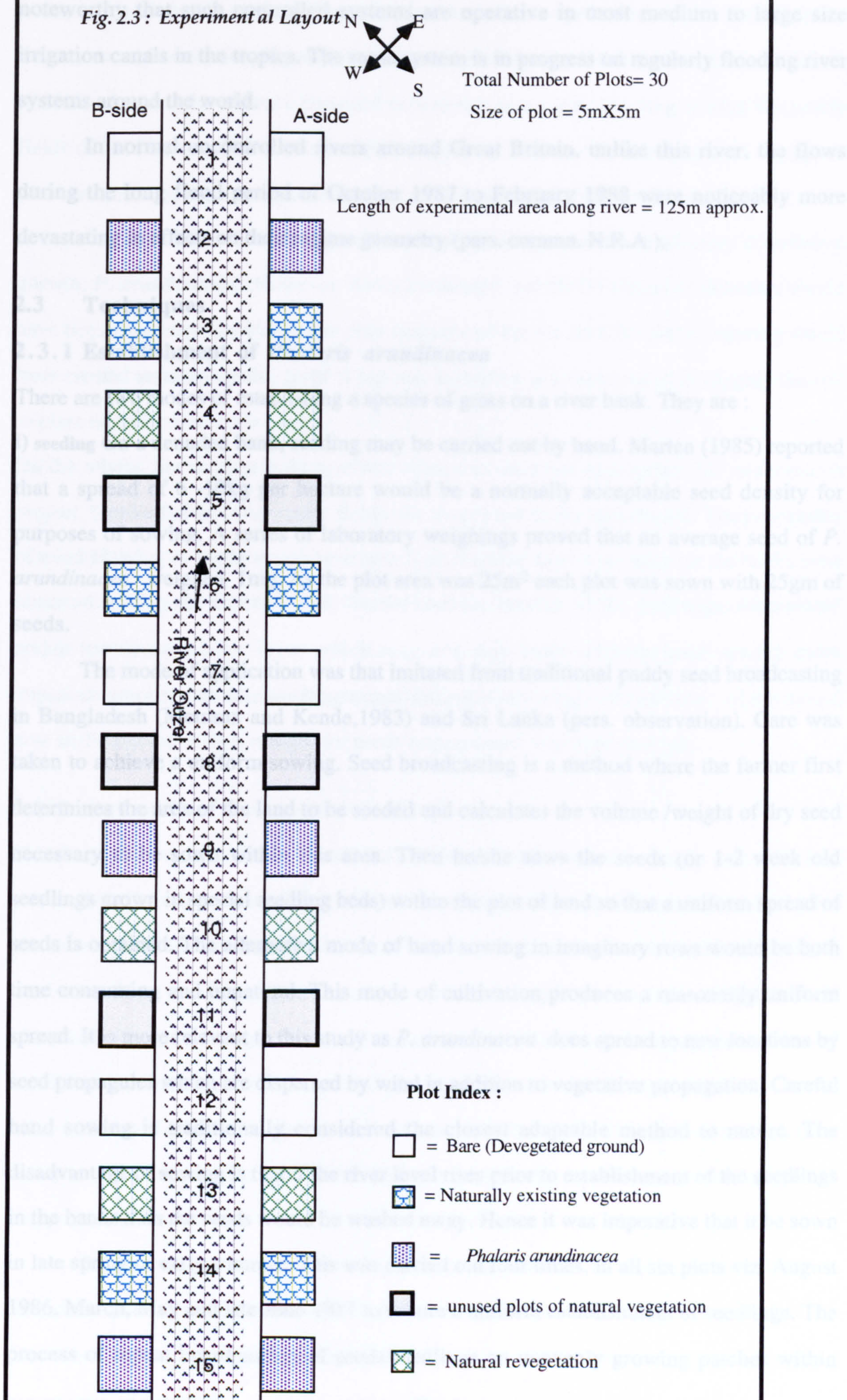
Treatments for *Experiment 3* : (a) Artificially denuded banks;
(b) Naturally re-vegetated banks;

There were six naturally vegetated plots (5a, 5b, 8a, 8b, and 11a, 11b).

2.2.4 Telemetric control of the river flow, and its influence on this study

A factor that may have significant effects on the regime of this stretch of the river is that the flow is controlled at different times by a telemetric system between Caldecotte (c. 2km upriver) and Willen (c. 1/2 km downriver). (see: Fig.2.1). At both Caldecotte and Willen there are large artificially constructed balancing lakes. The idea is to divert the excess water from the river at flood levels (storm flows) so that the area of land on either side of the river is never flooded by the control of the balancing lakes at high flow periods. It is

Fig. 2.3 : Experimental Layout



noteworthy that such controlled systems are operative in most medium to large size irrigation canals in the tropics. The same system is in progress on regularly flooding river systems around the world.

In normal uncontrolled rivers around Great Britain, unlike this river, the flows during the long flood period of October 1987 to February 1988 were noticeably more devastating in effects on their regime geometry (pers. commn. N.R.A.).

2.3 Techniques

2.3.1 Establishment of *Phalaris arundinacea*

There are two modes of establishing a species of grass on a river bank. They are :

i) seeding On a denuded bank, seeding may be carried out by hand. Marten (1985) reported that a spread of 6 -10kg per hectare would be a normally acceptable seed density for purposes of sowing. A series of laboratory weighings proved that an average seed of *P. arundinacea* weighed 1mg. As the plot area was 25m² each plot was sown with 25gm of seeds.

The mode of application was that imitated from traditional paddy seed broadcasting in Bangladesh (Metraux and Kende,1983) and Sri Lanka (pers. observation). Care was taken to achieve a uniform sowing. Seed broadcasting is a method where the farmer first determines the area of the land to be seeded and calculates the volume /weight of dry seed necessary to be sown within this area. Then he/she sows the seeds (or 1-2 week old seedlings grown in special seedling beds) within the plot of land so that a uniform spread of seeds is obtained. The alternative mode of hand sowing in imaginary rows would be both time consuming and unnatural. This mode of cultivation produces a reasonably uniform spread. It is more relevant to this study as *P. arundinacea* does spread to new locations by seed propagules which are dispersed by wind in addition to vegetative propagation. Careful hand sowing is traditionally considered the closest adaptable method to nature. The disadvantage of sowing is that if the river level rises prior to establishment of the seedlings in the banks then the seeds would be washed away. Hence it was imperative that it be sown in late spring or early summer. This was carried out four times, in all six plots viz. August 1986, March, May and late June 1987 to ensure a uniform establishment of seedlings. The process of repeat broadcasting of seeds/seedlings on unevenly growing patches within

paddy cultivations is a common practice. The theoretical expectations of the ultimate plant density would be in keeping with the law of self thinning ($-3/2$ power law of Yoda et al,1963). In fact, the author's personal experience as a youth growing among the paddy fields of Sri Lanka is that both density and apparent heights of paddy plants in any given plot was uniform, even though the farmers were ignorant of Yoda's self thinning law.

2) layering of rhizomes This is a good method for establishing a uniformly distributed growth. *P. arundinacea* . However, it was calculated that 60000 pieces of rhizomes would have been necessary for planting at 5cm spacings on the six 5mX5m plots. Layering would have created an unacceptable level of top-soil instability as a direct result of digging the soil to plant the rhizomes in the banks.

On the whole, the seeding technique was chosen as the more appropriate for this research project. Unlike flat and wet paddy fields, the river bank is dry and sloped. The probability of wind-blowing of seeds would have been high if all the dead vegetation on the banks were removed leaving the exposed bank. On the contrary leaving all the dead vegetation would create too dense a litter layer which may not only make uniform seed sowing more improbable but also hinder seedling establishment. Only a light mulch cover which would give sufficient moist dark refuges for seeds to germinate, was therefore left.

2.3.2 Denudation of vegetated banks

There were two options for the denudation of the plots that were to be made bare. The first was to mow the vegetative foliage either mechanically using a trimmer or manually by the use of a pair of shears. This would mean that the live roots would be left in the soil. It would invalidate the idea of total denudation of banks. Any live roots left in the ground will affect both the shear strength of the soil and erodibility of the bank. Besides, the problem of rapid recolonisation from underground plant matter such as rhizomes and buds, would involve repeated denudation almost on a monthly rota during the Spring, Summer and early Autumn. As such the idea was abandoned as scientifically unwise and methodologically inappropriate.

The alternative mode of denudation is the application of a systemic herbicide as frequently practiced by land owners and farmers (Haslam,1981). Extreme care has to be exercised in the choice of the herbicide due mainly to their inherent toxicity to man and

animals in addition to possible devastation of the riverine ecosystem. As the application is governed by statutory law, the Garden Superintendent of the Open University helped with the preparation and spraying of the herbicide. Permission was sought for this activity from the Milton Keynes Development Corporation (land owner) and the Anglian Water Authority.

The systemic herbicide used was Round Up from Monsanto Ltd. It contains 480 g. per litre of N-phosphonomethyl glycine as the isopropylamine salt (equivalent to 360 g. per litre glyphosphate). It is a foliar applied herbicide for the control of annual and perennial grass and broad-leaved weeds before sowing or planting of all crops. It is translocated from treated vegetative growth to underground roots, rhizomes or stolons. The application mixture was as prescribed by Monsanto : 4l/ha with a water volume of 200-250 l/ha.

The time of application of the systemic herbicide was chosen so that the weather forecast would be dry and sunny for at least three consecutive days, as prescribed by Monsanto. As the experimental plots (see Fig.2.3) were marked out in May 1986, and the weather was unreliable up to mid-June, it was on 16th June 1986 that the first application was possible. The post-application period for the herbicide to be fully effective is between 7 and 10 days. Eighteen of the thirty plots were denuded. The plot numbers were: 1A, 1B, 2A, 2B, 4A, 4B, 7A, 7B, 9A, 9B, 10A, 10B, 12A, 12B, 13A, 13B, 15A, 15B.

2.3.3 Measurement of Shear Strength of the banks

Ideally both cohesion (C) and the angle of internal friction (ϕ) must be quantified in a given soil to identify its shear strength properties. This arises from the Mohr-Coulomb equation :

$$\tau_{\max} = C + \sigma \tan \phi$$

where τ_{\max} = maximum shearing stress (kPa);

C = cohesion of the soil medium (KPa);

σ = normal stress (kg m^{-2});

ϕ = angle of internal friction of the soil;

There is considerable criticism of Mohr's classical equation. For example, Johnson et al (1983) note that in actual practice a linear failure envelope may not adequately describe the actual shear behaviour of the soil. Kassif and Kopelovitz (1968) used a double shear

apparatus to quantify the shear strength properties of root permeated soils. Unlike Kaul (1965) who used a matrix of millet roots grown in a growth chamber, Kassif and Kopelovitz used synthetic fibre made of 80% P.V.C and 20% di-octyl-phthalate. These were embedded vertically in two types of soil. Furthermore, they fixed one set of fibres to a base while the other set was without 'fixity'. While the study was directed at an understanding of root permeated agricultural soils to a cutting tool, the effects of increase of shearing resistance by roots in soils was conclusively observed. As the authors themselves conclude this type of simulation of roots by synthetic fibres 'suffers from limitations'. As much as Kaul (1965) demonstrated a similar increase in shear strength with his millet roots that grew under controlled laboratory conditions, his results were not superimposable due to the extreme variation in the homogeneity of the samples.

One factor of significance from Kaul's study was that the friction angles (ϕ) of the soil samples with roots had a larger magnitude when compared with similar soil without roots. This is ascribed to 'the action of rootlets making larger virtual particles out of smaller ones'. Even though there is no comment or criticism of this postulate in subsequent literature it is worthwhile discussing the possible implications of such a phenomenon on existing theory and the practical implications.

Kaul's suggestion that plant rootlets tend to make larger virtual particles out of smaller ones has to be read in conjunction with the following:

- a) it is highly possible that rootlets actively contribute to increased cohesion of soil particles by root exudates (Reid and Goss, 1980, 1981) which have constituents such as mucopolysaccharides that have a highly adhesive nature;
- b) an increase in the angle of internal friction increases the critical levels of stability of the soil; as such this proposal contributes to the validity of using Coulomb's Law for measurement of shear strength of the soil.
- c) It is uncertain as to what is meant by 'rootlets'. In plant biological terms these are physiologically highly active organs of the plant which may be minute in size (Bohm, 1979). If size is a criterion in recording the total effect of the rootlet in resisting shearing forces then the currently accurate instruments of 'direct shear' may not be suitable. This is because the rootlets are so minute that they may not offer the tensile resistance to planar shearing

devices. Whether the rootlets are fixed to the plant or an artificial base the shearing device would have to be extremely precise in addition to being minute. In addition the rootlets are distributed in a network of ramified orientations (Bohm, 1979). Such diversity in orientation greatly reduces the applicability of the fundamental theoretical model (cf. Waldron, 1977) on the effects of plant roots on shearing stress which is based on a vertically oriented root being subjected to horizontally applied direct shear. Waldron and Dakessian (1982) observe that grassy species including *Phalaris tuberosa* produced a denser root matress and higher shear strengths in a short period of growth when compared with pine saplings of similar age. They propose that the higher soil stability ascribed to tree species as opposed to grasses in the field situation is due to both tensile properties of their roots and their ability to 'extract more water from a greater depth than does grassy vegetation, so that where trees are present, the onset of saturation requires more rainfall'.

The inclusion of the latter hypothesis compounds the complex nature of soil stability studies on a river bank slope with a mixed vegetation (leading to complexities in root tensile properties, root density at different depths etc.) and a moisture profile gradient up the bank which itself is variable in keeping with both the flow levels and precipitation.

Unless shear strength variations in a particular soil are to be studied very accurately, such as the effects of varying normal stresses within a short range of stress values, it is not necessary to use more sophisticated shearing tests such as the Triaxial test, direct shear boxes. Torsional shear devices such as the Cohran sheargraph (Cohran, 1962) may have been useful as soil cohesion and friction angle can be quantified in situ. Such a technique would facilitate a more detailed study of the above parameters so that the bulk shear (as opposed to planar shear stress) resistance (see 2.3.5 and Fig.2.5 for further explanation) can be related to total root length within the sheared volume and not root area ratio within the planar surface of a direct shear device.

In the absence of the above options, this study encompasses measurements of shear strengths on a comparative basis where the effects of roots of vegetation is the main theme. Shafer et al, (1963) and Johnson et al, (1983) discuss the various shearing apparatus useful for various scientific needs. Thorne (1978) discusses the advantages and disadvantages of using different shear apparatus for a study of river bank soil. Equipment such as the

Penetrometer or Hand Shear Vane which is simple to use in the field are recommended where comparative effects due to a particular factor in soil are considered. The only factor we are quantifying in this study is maximum shearing stress that the bank soil tested can withstand.

N.B. : All readings of shear failure above 120 kPa cannot be read on this type of Shear Vane as the Vane head meter reads only upto that value. This is noted by Thorne (1978) and values at 120kPa are treated as above 120kPa.

Within the available resources, a Shear vane was borrowed from Silsoe College, Bedfordshire. The Shear Vane used was an ELE Hand Vane Tester (ELE International, Eastman Way, Hemel Hempstead, Hertfordshire, HP2 7HB, England). The Shear Vane has two alternative vanes, one 19 mm (with a range of 0 to 120 kPa) while the other is 33 mm (range of 0 to 28kPa) in diameter. This type of shear measurement device has been used by other researchers for similar studies on river banks (Thorne, 1978). Another advantage is that it gives a direct reading *in situ* at a given depth.

The number and frequency of shear strength readings per plot was determined on the basis of:

- a) within plot variation in soil and varying moisture content up the bank;
- b) time considerations of feasibility of operation by a single person;
- c) seasonal variations; in order to monitor variation in shear strength related to plant growth and decay, readings were taken in August 1986, February and August 1977, February, May, and August 1988; seasonal variations in moisture content are associated with the expected high flows in winter and the low flows of summer. But summer floods are possible (see Figs. 3.1a and 3.1b)

In a preliminary trial, adaptation to the equipment and the time consumed per test was carried out in June 1986. An attempt was made to study the shear strength at every 50cm up the bank together with readings at 1m, 2m 3m and 4m, laterally from the edge (0m) of each plot for eight plots. In addition to plots 1a, 2a, 3a, and 5a, plots 1b, 2b, 3b, and 5b, were subjected to shear strength and moisture content measurements in August 1986. This was primarily to identify any significant differences in the measured soil properties on banks on opposite sides of the river. As there were no significant differences

and the possible destruction arising out of sampling in too many plots (see 2.3.6) may introduce an experimental error on erosion readings of these plots, it was decided to limit sampling to plots 1a, 2a, 3a and 5a only. In addition, it was obvious that such an intensive study was detrimental to the long-term interests of the research proposal due to the following reasons:

- a) due to the unpredictability of the weather changes in Britain, each period of shear strength and moisture content measurements had to be carried out within three days; these were chosen as clear sunny periods with nil or minimum rain over the previous week; any overnight precipitation or drastic changes of weather would yield a high variability of results; they would inevitably undermine the main objectives (effects of different vegetations) of the shear strength /moisture content.
- b) it consumed too much time; more than three hours per plot;
- c) trampling on a vegetated slope or on a friable soil slope of a bank can seriously affect the vegetative growth and can cause experimental error by soil slips and involuntary damage to the slope surface on bare soil.

It was decided to facilitate a statistically valid analysis by taking at least three shear strength measurements at three positions on the vertical levels (see Fig.2.4). 1/6th the area of the total treatment is regarded as sufficiently representative of its sub-characteristics (main characteristics and objectives of this study were changes in rates and amounts of erosion under the different treatments).

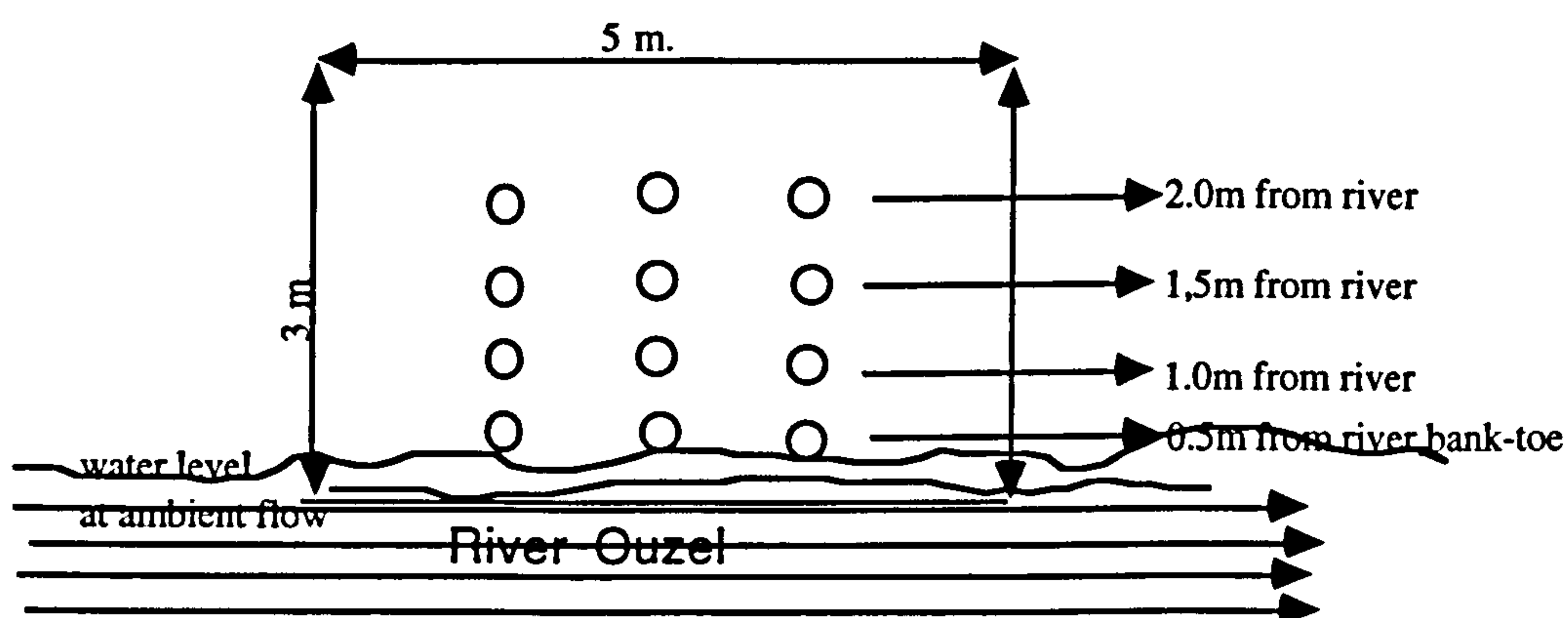


Fig.2.4 : Positions of shear strength, Moisture content and Root-core sampling;

Plot size = 5mX3m; ○ = circular area of approximate radius of 25cm within which all samples were taken;

Reasons for taking shear strength values after allowing for the ground to dry after rain

In this study there were two phases of the erosion concentrated on:

- (a) **Winter erosion** the highly erosive, generally wet river corridor with a high frequency of changes in the flow levels;
- (b) **Summer erosion** the least erosive, generally dry, summers with a low frequency of changes in the flow levels (see Figs. 3.1.a and 3.1.b).

N.B. the relatively high maximum discharge in June-July 1987 (see Appendix 2) was due to Anglian Water controlling the telemetric system so that Willen Lake situated around 800m down river would be adequately filled and not due to a natural flood occurrence following a heavy precipitation.

In this study, any measurements of shear strength and moisture content on the banks during the summer period would have led to a complex and unnecessary series of problems in data analysis and interpretations if these were carried out during or immediately after any summer precipitation. The complexities would have arisen because shear strength of a soil at any given time is directly dependent on the moisture content in the soil at that time (Ohu et al, 1976). The highly infrequent and intermittent summer precipitation was a 'transient phase' of hardly any value within the scope of this study. The reason is that this study is concentrated on inter-seasonal rather than intra seasonal complexities. As such, the simplest mode of avoiding unwarranted complexities was to let the banks dry out after the usually short spasms of summer rain if any and then carry out the shear strength moisture content and root density sampling.

In essence, variations of shear strength of the banks under varying hydraulic regimes (and root density) is a key aspect of this study. Variations of shear strength under varying surface precipitation regimes would disorient the shear values (in analysis of results) during low hydraulic flow regimes.

2.3.4 Moisture Content Measurements

As mentioned in 2.1 and 2.2 above, moisture content varies upwards along the profile of the bank at ambient flow. The most accurate form of permanently installed apparatus for measurement of moisture content at regular intervals in the field, would be

using the tubes that are part of the Neutron Hydroprobe. While this instrument has obvious advantages in accuracy, rapid measurement, portability, and has a microprocessor incorporated in the probe that allows 279 records to be stored with a typical format of one calibration, one key data and three depths, it also has the disadvantages of being expensive, needs special radiological licencing, and may not be suitable for depths of less than 15cm from the soil surface. The latter disadvantages clearly ruled out the use of this equipment for this research site.

Other instruments such as the Quickdraw soil moisture probe and soil moisture meters with soil moisture cells were considered. Due to their unavailability, wet and dry weight sampling was adopted even though it is a laborious process. The procedure is to collect a sample of soil as close as possible to the position of shear strength measurement, using a soil corer which is a 2cm diameter steel tube with a cutting edge. This was made in the University work shop. The soil corer is driven into the ground at a perpendicular angle to the immediate soil surface and to the same depth at which the shear strength measurement was taken.

Three samples per position of shear strength measurements (see Figure 2.4) were taken. The reasoning for the shear strength measurement regime as discussed above applies for the moisture measurement regime as well. The mean of the three values per position was plotted against the same for shear strengths as shown in Chs.3, 4, and 5.

To ensure that the moisture sample is from the same depth as the shear strength measurement area, the soil core at 10 -12cm depth is squeezed out using a wooden baton. As it is squeezed out the bottom end of the core is cut at 2 to 3cm length into a sealable polythene bag with the appropriate label representing the position and the plot.

The contents were stored in the sealed polythene bags at -20° C in the deep freezer until (within 2-3 days) the contents were emptied into pre-weighed brass boxes with air-tight sealing lids. After weighing the boxes with the undried sample of soil, the boxes were stored in an oven (Gallenkamp oven/sterilizer) preheated to 110° C, taking care that the lids were removed and placed underneath the relevant box. Samples were left to dry for 24 hours. Each box was then closed tightly with its lid and placed in a desiccator with desiccant to ensure that the sample did not absorb any moisture from the air in the cooling process.

The cooled boxes plus dry samples were weighed and the drying process repeated for a further 24 hours at 110° C. Preliminary experiments showed that constant weight was achieved after one to two periods of drying and two was adopted as standard before calculating the % moisture content.

2.3.5 Root Length Measurements

As mentioned in 2.1. above the necessity was to quantify the possible amount of total root length that was present in the cylinder of soil that was subjected to shear while using the shear vane for shear strength determinations. The diameter of the small vane is 1.9cm, while that of the larger vane is 3.3cm. The height of the small vane blade is 3cm. Therefore it would be fair to presume that the root area measured is approximately equal to the cylinder of soil in which the shear strength was measured.

The number of samples to be taken as representative of the treatment were based on an appreciation of the following critical factors :

- i) the need to carry out three bank destructive sampling processes concurrently ; i.e. gather soil cores for (a) moisture content and (b) root sampling, together with (c) causing shear failure by the use of a hand shear vane of 3.0cm diameter steel blades; all three processes inherently carry with them an artificially created factor of increased erodibility (see 2.3.6);
- ii) soil disturbance created by the extraction of the number of samples (see 2.3.6);
- iii) acceptability in terms of soil core size for root sampling in field experiments in comparison with similar work done by other researchers ;
- iv) vegetation destruction (in vegetated banks) and bank instability (in bare banks) created by excessive trampling pressure while sampling.

Some criticisms of the available techniques:

In attempts to relate the effects of roots on the variations of shear strengths of different soils, there have been three broadbased attitudes to quantification of roots.

i) mass of roots per unit volume of soil (Endo and Tsuruta,1969) :

This takes into account the weighing of the sum total of roots in a given sample of soil. In theory, it is a reasonable parameter for quantification. But, in practice, it is beset with problems. Some of the problems are (a) the inability to collect/separate all the minute roots in the sample, especially when the sample is large; (b) the inclusion of dead roots in

weighing. This can be a source of error as the relationship of a live root to the shear strength of the soil may vary a great deal from that of a dead root. As a root dies it loses its stress-strain characteristics (O'Loughlin, 1974; Brenner and Sai-Ming, 1977).

The theoretical principle of increased shear strength (Wu et al, 1979) on which the civil engineers base their relevance of the effects of roots is questionable. The main debatable issues will be:

- a) that not all roots are vertically oriented in the soil;
- b) the variation of diameters and the differential tensile properties of the root layers such as the outer cover and the stele. In work done by others (cf. Endo and Tsuruta, 1969) using the mass of roots per unit volume there is insufficient discussion of the above possible anomalies.

ii) Root area per cross sectional area (Waldron, 1977)

This quantifies the ratio of the total cross sectional area of roots within the soil core at the sheared cross section. It is a time consuming and cumbersome task with some of the disadvantages met with in (i) above. For example, there is the possible anomaly due to the presence of dead roots which may have lost the mechanical properties present in a live root of the same diameter and species of plant. Staining may be difficult with the colour of the soil overshadowing the stain. However the advantages are also considerable. The fact that in shearing a sample in a shear box, one expects a planar cross-sectional shear rather than total distortional shear of a soil cylinder, the root area per cross sectional area method is considered adequate.

iii) Total root length of the sheared soil cylinder (Tennant, 1975)

This is a technique mainly used by plant physiologists as Tennant himself mentions. Others such as Reid and Goss (1980) have used it for soil aggregate stability studies. In fact, it not only differentiates between dead from live roots but also quantifies the total root length within the sample. This encompasses a whole spectrum of available roots from the microscopic to a few millimeters in diameter. While the author realises that there is criticism of the suitability of the hand shear vane in determining the shear strength of soil with roots, the use of this technique to measure the total root length in the sheared volume of soil may nullify some of the criticism. As shown in the Figure 2.5. below, the aim is to

quantify the total root length within the cylindrical area subjected to shear distortion by the shear vane. As opposed to the shear box where it is subjected to planar shear, the shear vane subjects the soil to bulk shear. The resistance to this shearing force is offered by the soil plus the mechanical resistance offered by the roots and most probably by the cohesive forces between the root/soil binding root gel. There is hardly any mention made of the last aspect in literature on the effects of roots of plants in affecting shear strength of the soil. It may well be a considerable aspect in the 'cohesive factor' C , in the classical equations of measuring shearing resistance of soils.

Mohr's Theory has to account for C as a cohesion factor consisting not only of cohesion between soil particles (C_1) due to moisture, but also due to another factor (C_2) due to the exudates from roots (see 1.5 and 2.3.3).

Hence: $\tau_{\max} = (C_1 + C_2) \sigma + \tan \phi$

Even though C is not necessarily quantified for the aims of this research study, this additional factor may be better reflected in using Tennant's technique than that of bulk root weight or root cross sectional area. In the process of being subjected to bulk shear as opposed to planar shear, the effects of the adhesive properties of root exudates will be more evident. Therefore the shear vane can be considered advantageous for this type of work.

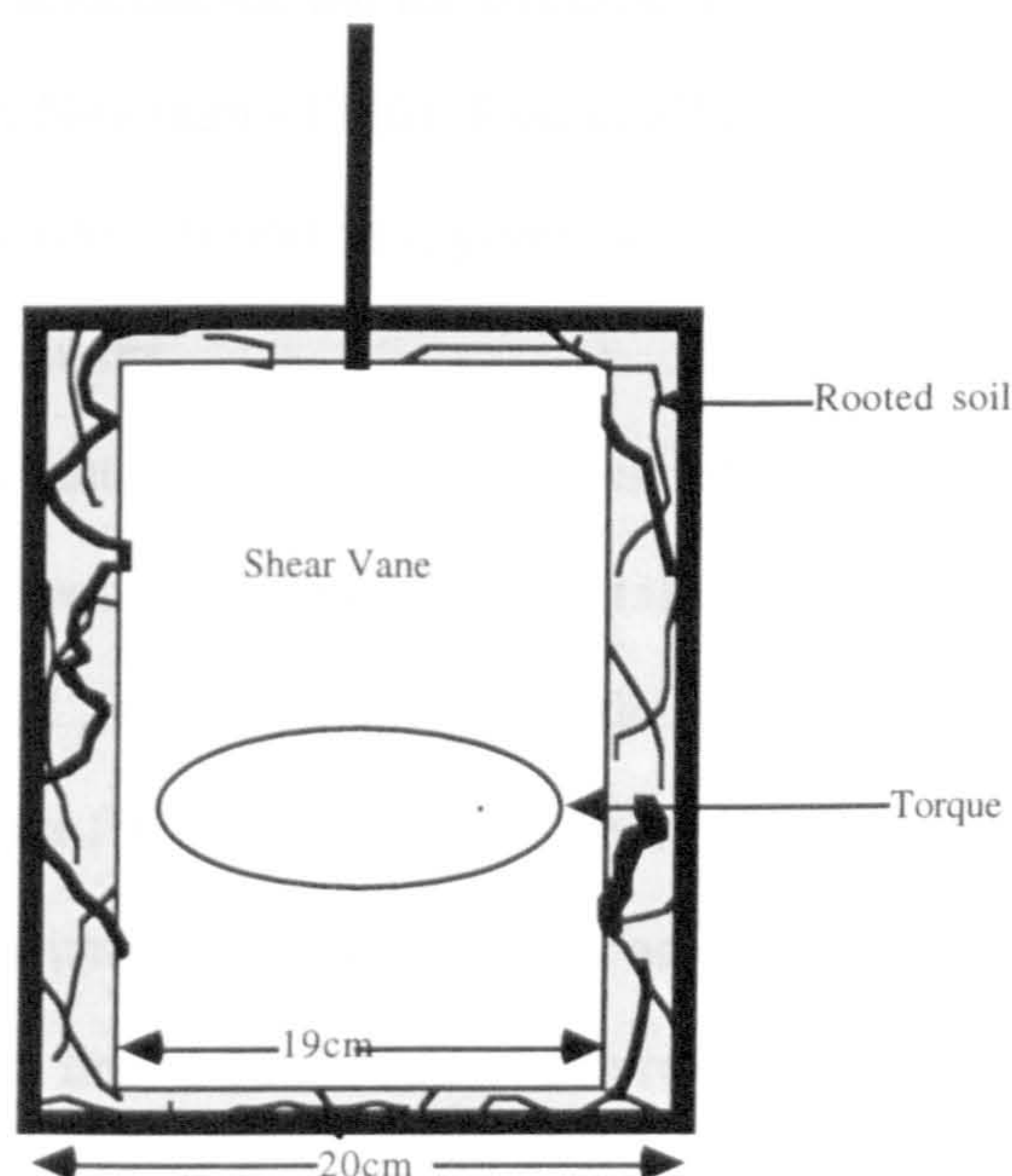


Fig. 2.5 Diagrammatic C.S. of a soil cylinder sheared by a Vane

The problems associated with estimation of root length or density in the field situation are twofold:

i) Singh et al (1984) simulated net primary production of root biomass in a grassland. Calculations of below ground net production revealed substantial sources of error. They estimate that such errors may be common in estimates of below ground net production in field data. This is attributed to 'inherent bias in the most frequently used estimators and a counter-intuitive effect of sample variability'. They set out to test the hypothesis that under-estimation is the norm but, in fact, the reverse was true.

Hence, it may be that the conclusions arrived at so far relating high shear strengths to high root densities may not be so valid in the field situation if there is less root density at different depths .

ii) Kershaw (1980) discusses the variations of above ground biomass estimates with reference to possible non-uniform distributions of the individual plants in a given area of land. His argument is applicable to the below ground situation in the same manner if not worse. The reason is that rooting patterns vary between species (Gray,1974) and root colonisation is dependant on soil nutrient status, aeration and other physical characteristics to name but a few.

The technique selected for the measurement of total root length was that of Tennant (1975) modified from Newman (1966). Essentially it consists of counting the number of intersections made by roots found in a given soil sample on a 10x10cm grid that is subdivided into 1 x 1cm squares.

It was decided that a cylinder of soil 2cm in diameter and of length 2.5cm, would suffice to indicate the root area of the samples taken for this study. As such, using the soil corer described in 3.2.2., a core of soil from the position of shear strength measurement was squeezed out into a PVC tubing. This tubing has an internal diameter of 2cm and a length of 2.5cm. The transfer process takes an appreciable amount of time (2mins. approximately) as care has to be taken not to press too much soil from the initial sample core into the PVC tubing. Once the specimen sample is prepared, it is transferred to a sealed labelled polythene bag. This can either be stored in the refrigerator overnight prior to

washing and root length measurement process. Trials proved that the roots may be kept in live condition in the refrigerator for 3 to 7 days.

Washing roots from the soil samples was carried out in a 250ml. conical flask. 50 to 70 ml. of water was added to the flask, which was shaken gently to disperse the soil particles in such a manner that all roots were isolated. The mixture was then filtered through two brass sieves of mesh size 1.0mm and 0.25mm.. A light jet of water was sprayed on the sieves to wash away the soil particles, leaving the roots. Forceps were used to transfer all the roots to a clear plastic vial containing distilled water. Extreme care was needed to pick up all the minute roots, using a x 10 magnifying glass. These plastic vials with their contents were closed with the cap and either stored in the refrigerator overnight or the contents were poured into the plastic petri dishes for root length counts. The differentiation between dead and live roots was facilitated by the use of 0.2% aqueous solution of eosin red as recommended by Bohm (1979).

The procedure followed thereafter was as described by Tennant (1975) for counting total root length in a sample of soil but the apparatus for the root counting process was modified. The author realised that a microbial Colony counter available in the laboratory was adaptable for ease of operation, better optical facilities and a clearer observation of roots on the sampling grid. The grid used was made in the workshop of the University using plastic sheets cut to the specification mentioned by Tennant.

Tennant's formula used for the measurement of total root length:

$$\text{Root length (R)} = 11/14 \times \text{Number of intercepts (N)} \times \text{Grid unit}$$

The 11/14 of the above equation was combined with the grid unit to give a length conversion factor. For a 1cm grid square the length conversion factor becomes 0.7857. Therefore the modified form is :

$$R = 0.7857N, \text{ where, } R \text{ (in cm) is the total length of root in the sample of soil.}$$

2.3.6 An estimate of possible bank soil disturbance due to sampling of shear strength, moisture content and root density in the experimental area

i. Destruction of bank soil in relation to the usage of the Shear Vane

The larger vane head which was used for measuring low shear strength values (i.e. mostly the 0.5 and 1.0m from bank-toe) had a diameter of 3.3cm.

Therefore, in the very process of inserting the vane head into the soil it covers an area of $(3.3 / 2)^2 \times (22 / 7) = 8.56\text{cm}^2$ soil surface. (10cm^2 approximately); The actual destability is much more as the process of insertion and torques of the vane causes destability of at least another 1cm along the circumference.

If the sampling regime is that of taking three samples per position, and one plot has twelve such sampling positions (see Fig. 2.4) the total surface area destroyed = $10 \times 3 \times 12 = 360\text{cm}^2$ per plot.

ii) Destruction of the bank by moisture content sampling

The outer diameter of the soil moisture sampling corer was 2.5cm. The total cross sectional area covered by this on the same formula of πr^2 (as for the shear vane) where r is the radius of the core, $((2.5 / 2)^2 \times 22 / 7 = 4.91\text{cm}^2)$ is 5cm^2 approximately. For twelve sampling points at one reading per plot it destroys a total area of $5 \times 12 = 60\text{cm}^2$.

iii) Destruction of the bank soil by root sampling

The outer diameter of the core sampler was 2.5cm. Therefore, the total area destroyed per plot at one root sample per position = 60cm^2 .

On the whole, at this minimal level of sampling itself the total surface area destroyed would be a minimum of $(360+60+60) 480\text{cm}^2$ per plot. The effective area of each plot under investigation for erosion studies (which is the main theme of this study) is 200cm height \times 500cm width = 100000cm^2 .

Therefore, the percentage area destroyed by the above sampling regime is :

$$480 / 100000 \times 100 = 0.48 \% \text{ per plot.}$$

The damage would be greater if the following facts are accounted for:

- a) the depth to which each sampling equipment is inserted has to be taken into account as the above calculation is the minimal surface disturbance / destruction / instability caused;
- b) the proximity of the sampling (all three measurements had to be done within the immediate neighbourhood if not at the very same position) to each other ;
- c) the added trampling pressure caused by the person/s sampling both in terms of soil compaction and disturbance but also disturbance of vegetation which is critical for species such as *U. dioica*.

2.3.7 Action to negate possible causes of anomalous results

Some of the commonest causes of anomalous results in field experimentation arise from extraneous sources such as inquisitive passers by, dogs, and children. At the outset of the experimental layout these were identified. Before the plots were applied with herbicide, it was considered ethical to mark out the experimental area as an unsuitable area for humans or animals. It was therefore enclosed with fence posts and wired with clearly visible tapes. Subsequently, it was completely fenced in as shown in the Plates 4 and 10. This negated any anomalies such as trampling effects and digging up of the bank.

Bank morphology was a critical issue of relevance at the commencement of the experiment. Following a careful process of observation of the slope characteristics along the 800m of this reach of the straight channel, this 150m strip was selected as the most uniform profile. The initial assesment was based on numerous measurements of heights with reference points on the apex of the bank to asses whether any non-uniformity of the slope was evident. Perfection in the profile was an ideal not expected. Any subsidence was a main issue searched for in attempts to select the best available slope. An idea of the success may be gained from Plate 1. It shows the bare bank plots after application of the herbicide. The original fence posts demarcating the experimental area, mentioned earlier, are visible.

The process of keeping the denuded banks bare throughout the period of the study presented some problems. the first was that the National Rivers Authority and the Milton Keynes Development Corporation as land owners were averse to regular applications of herbicide on the river banks. This was remedied by spot application of herbicides at regular bi-monthly intervals.

Frost heave was carefully observed and periods of frost incidence were avoided for erosion pin measurements. This was the best method of avoiding severe damage to the bank surface that may otherwise be created by trampling while taking measurements. Regular observations were made during high wind periods especially during the dry periods in summer for signs of wind erosion. This phenomenon of potential source of experimental error was not observed at any time.

2.4. Erosion Measurement Techniques

Perfection of a technique for the measurement of erosion is an aspect that has brought complex problems for all geomorphologists. Essentially, the idea is to quantify the amount of soil loss per unit area of a given soil per given time period. Both surficial loss as well as vertical mass collapse have to be accounted for. These processes are prevalent in fluvial erosive processes on all gradients of bank slopes (Thorne and Tovey, 1981). Where general methods of erosion measurement are concerned, Lawler (1991) identifies three disadvantages in current erosion measurement methodology. They are: (i) underestimation of the dynamism of the contemporary landscape; (ii) imposition of great uncertainty on process inference and hypothesis discrimination; and (iii) permit only limited verification of erosion models of high temporal resolution. His concern on the dynamic nature of a site in terms of erosion and deposition as two sequential processes dependant on the forces acting on the site acting at any given time were foreseen in this study (see 2.4.1 and Fig. 2.9.).

(a) Resurvey of Bank line This was a simple technique of either re-survey of original bank line using fixed reference points or the resurvey of channel cross sections (Wolman, 1959).

(b) Sequential Ground Photography Ideally, this process involves taking photographs at frequent intervals from fixed survey positions. It encompasses sequential ground stereo-photography as described by Simons et al. (1979). But Hooke (1977) discusses the practical limitations of this technique for a post-graduate study.

(c) Aerial Photography This is ideally suited for large scale long-term projects for the study of actively eroding banks (Guy, 1981). Landsat images have been used in recent studies to study bank shifting along the River Brahmaputra in Bangladesh.

(d) LEMI Toy (1983) compares a new technique of erosion measurement named, the linear/elevation measuring instrument (LEMI) with the conventional technique of using erosion pins. He concludes that the latter technique is more precise as well as being much cheaper.

2.4.1 Erosion Pin Technique

The most common technique used is the Erosion Pin Technique (Wolman, 1959; Twidale, 1964; Hill, 1973; Knighton, 1973; Hooke, 1977; Thorne, 1978). Hooke (1977a)

discusses the aspects involved and concludes that for the studies of corrasion and slumping the erosion pin technique proved satisfactory.

This technique utilises a long metal pin of mild steel with a diameter of 2 -15mm and 40 - 80cm long, driven into the soil at the position of erosion measurement. The pin is driven in such a manner that the tip lies in perfect line with the soil surface. As soil erosion occurs the pin is exposed, and its length can be measured using a millimeter ruler.

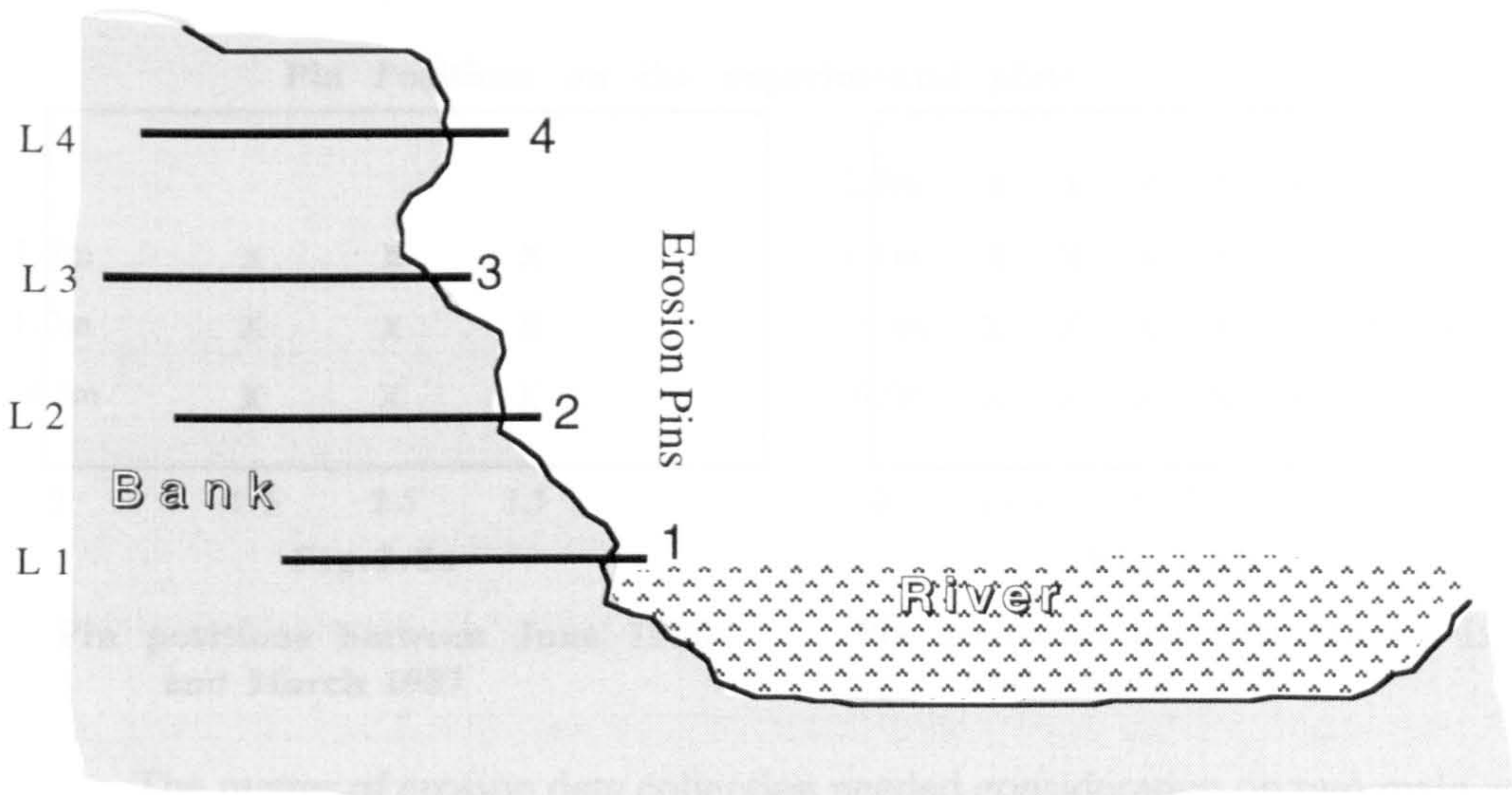


Fig. 2.7 : Erosion pins in position on the river bank

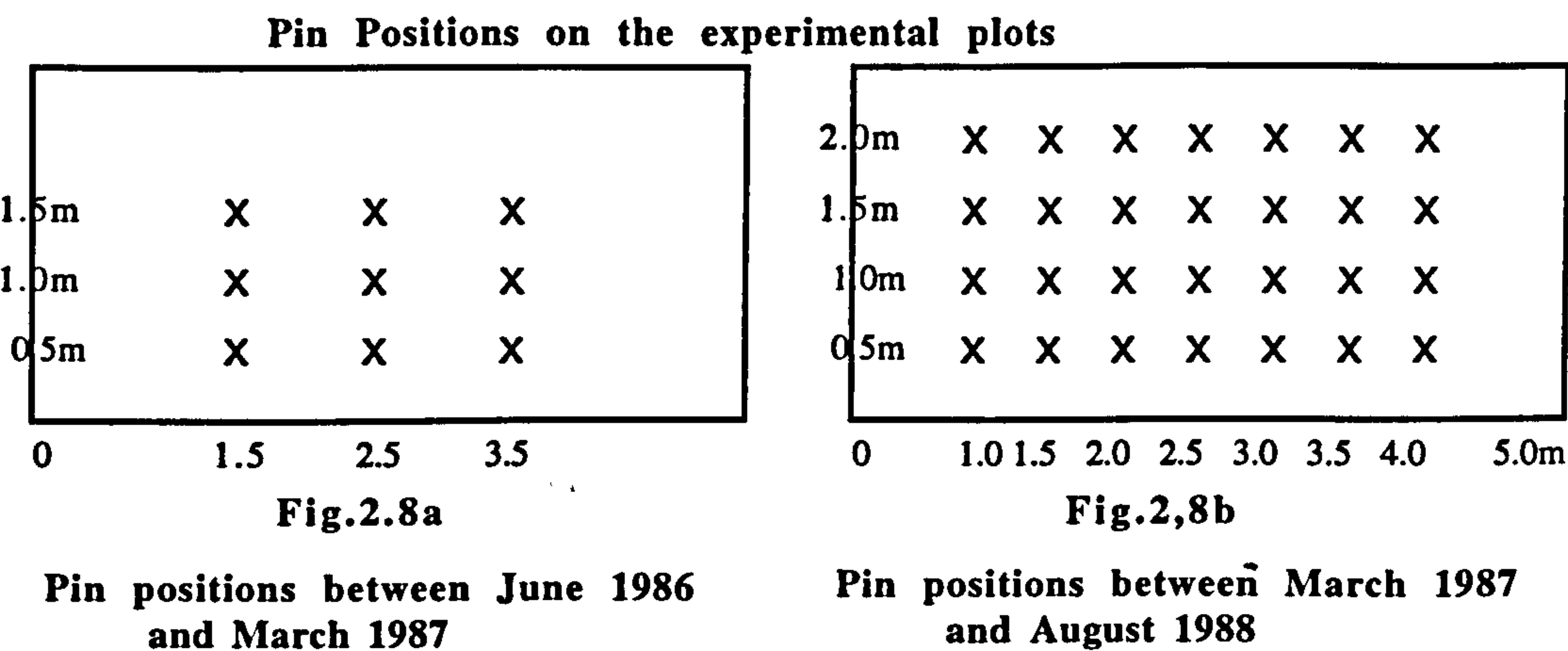
Pin 1 is approximately 50cm from the bank-toe
Pin 2 is 1m. from the toe; Pin 3 is 1.5m from the toe; Pin 4 is 2m from the toe;

There are many criticisms of this technique. Points of concern are:

- a) the presence of the steel pin in the soil may enhance the shear strength of the soil; On the basis of theoretical work done by Wu et al (1979) there is evidence for the reinforcement of the soil by fibres and metal rods inserted into a soil medium.
- b) how representative is the erosion around a pin which is expected to represent a scientifically valid sample of erodibility per unit area of soil at a given position on a flat or slope of soil?
- c) how effective is this technique on the base region of slopes where, as eroded soil from above falls and accumulates, the pin may indicate false readings? In some instances the pin may be completely covered by the aggradation process (see Fig.2.9).

However, in the absence of any newly developed appropriate technique, it was decided to use the pin technique on the slopes that were subjected to experimentation. The pins used were 3mm diameter mild steel rods of 60cm. length. These were driven into the

bank of the river on all thirty experimental plots. Initially, in June 1986, the pin regime per plot was nine pins per plot. Subsequently, it was decided that a higher number of pins per plot was needed to elucidate a more accurate representation of erosion of the slopes. This necessitated the introduction of pins both laterally and vertically on the bank as shown in Fig.2.8a. In the revised pin allocation there were twenty eight pins per plot. This represents an overall total of eight hundred and forty pins inserted on thirty plots.



The matter of erosion data collection needed consideration on two main aspects.viz:

a) time interval at which data should be gathered. It was possible either to read the erosion pins after discrete occurrences of changes in observed flow levels (and precipitation) or at discrete time intervals. As the latter was the more appropriate due to proven experience by others (Wolman,1959 ; Hooke,1977a ; Thorne,1978), and in ultimate evaluation of results, it was decided that monthly readings would be recorded as far as viable under the flow conditions prevailing or the national and regional weather forecast from the Department of Meteorology.

b) location of pins in plots covered with vegetation was forseen as a practical problem. As previous research (Smith,1976) suggests, erosion is usually minimal in vegetated areas. But, most authors genuinely abandoned attempts at erosion readings in vegetated plots due to the time that was consumed in searching for the pin tips and the difficulty of finding them in most instances (Hooke,1977a). Initially, the location of pins in vegetated areas proved difficult. A system of denoting pin tips that were not visible at first sight or not located at a particular recording event was devised. This proved useful as the records of the previous measurements indicated any problems of location of the pin on subsequent occasions.

In August 1986 when the 9 pin grid pattern was adopted (see Fig.2.8a.) three baseline marks were made at the top of the bank for identifying the vertical line downwards along the bank for location the erosion pin heads. This proved difficult to operate by one person who had to climb up and down the bank many times per plot in search of base line marks on the top and then the pin heads down the banks. Besides it proved almost fatal as clinging onto the inter-plot vegetation strips in attempts to climb up the bank resulted in the author falling in the river a few times! Later in March 1987 when the 28 pin per plot grid system (see Figs. 2.8a & 2.8.b) was initiated two systems were adopted in locating the erosion pin heads in the vegetated banks. They were :

i) the pin position was sprayed with a water resistant car paint (red) in an approximately 5cm diameter circle with the pin at the centre; This approach was adopted by Thorne (1978) on bare banks. On vegetated banks this was difficult to spray as great care was taken to lift up the foliage so as the spray did not kill them.

ii) the pin head itself was capped with a red plastic head barely larger than the pin head itself. This was allowed to protrude from the ground (approximately 2mm) and noted in the records. In some cases both methods were adopted together especially prior to winter flooding. In summer this approach helped to prevent considerable damage to the vegetation caused previously by trampling and handling vegetation in search of pins.

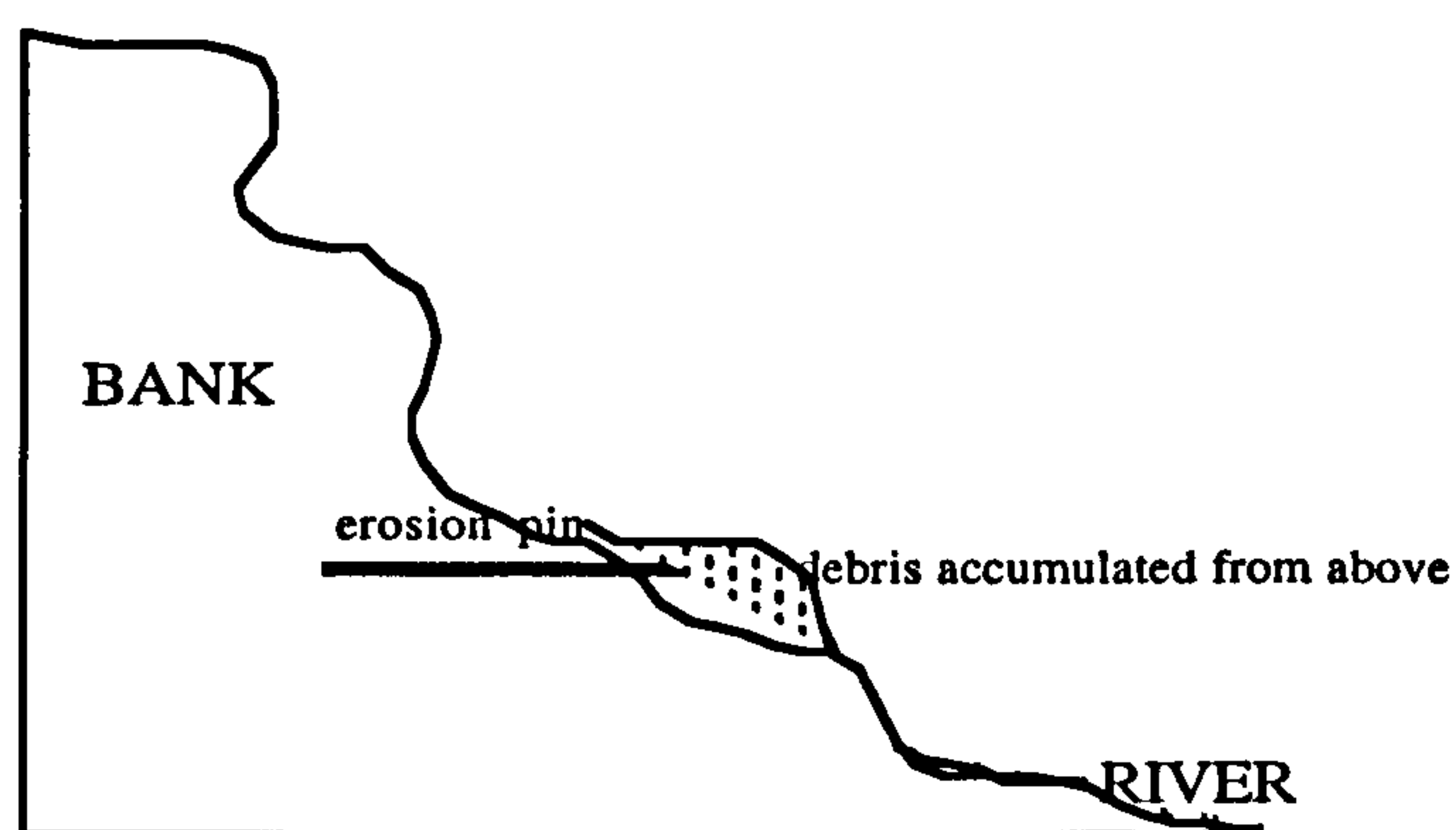


Fig.2.9 : Debris accumulation covering erosion pin

The following legends and their explanations proved useful as the system for field records:

C = pin covered by vegetation but tip visible; **C = 0** ; because the pin which was covered by vegetation in general and a stem, a leaf or even debris in particular merely covered the

erosion pin; The tip of the pin was in line with the soil surface on uncovering the leaf or vegetation.

N = pin not visible, possibly due to debris aggradation; $N = 0$; the pin may be covered by the aggradation of eroded soil from above, as mentioned earlier and shown in Fig.2.9 above. As the study is one of erosion and not accretion, only erosion is measured. The problem arising out of such a situation is that when such a 'covered pin' is exposed in subsequent erosion, the pin reading does not necessarily indicate the total erosion in a discrete sub-interval of time. It will indicate the erosion between the original zero position and the interval up to the erosion reading.

X = pin tip not visible, presumed lost due to slumping or unable to locate; **X** can not be treated as zero; pin may be lost due to slump failure and not corrosion. But, as the pins were 60cm long this was not feasible in this straight stretch of the river. Such mass failure has been noted for actively eroding rivers (Hooke,1977a; Thorne, 1978) It was not a frequent feature in this study. However for purposes of calculations this is treated as a missing reading. Hooke (1977a) reduced the problem of loss of pins in slumping by using longer pins (80cm).

$0 = 0$; pin tip is in zero position with no erosion visible; This is the theoretical ideal of no erosion.

As much as location of the pins on the banks was an important pre-requisite to measurement of erosion, there were certain foreseeable problems in interpreting data with the alternative situations.

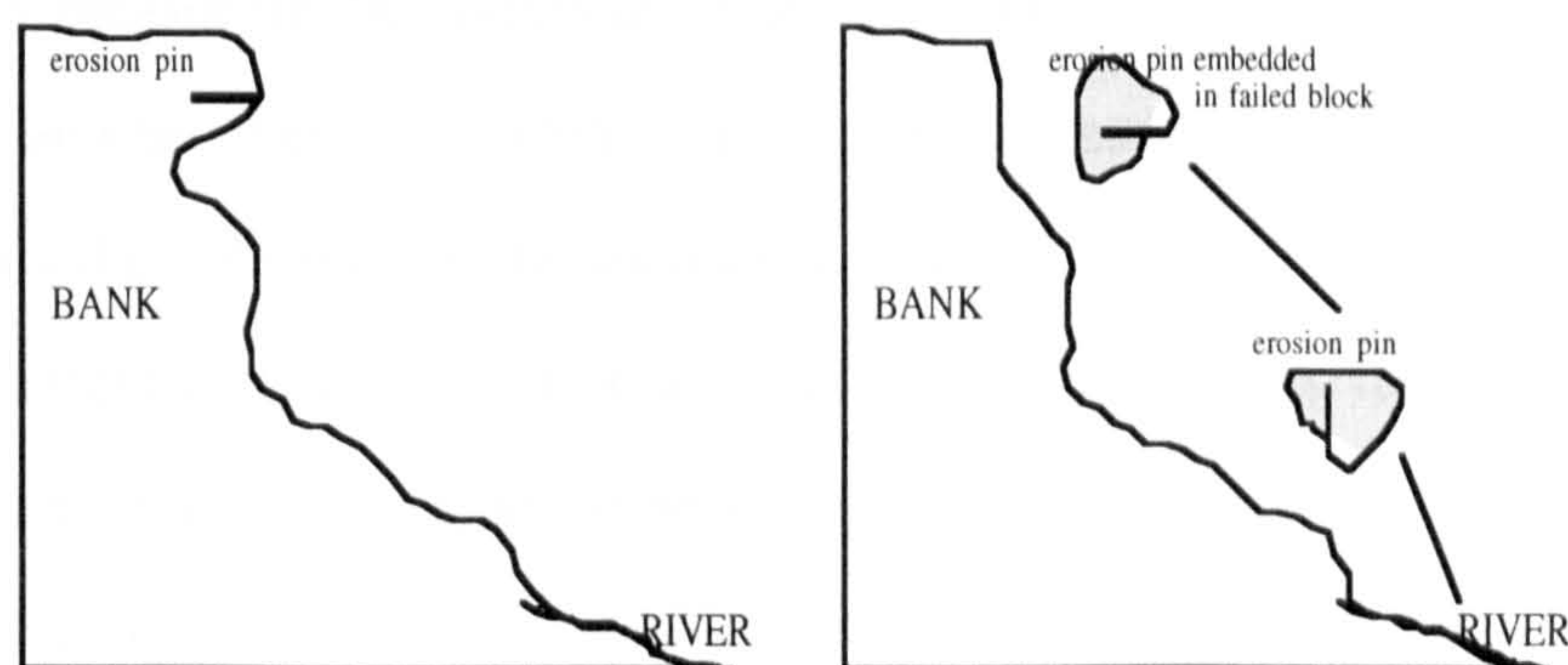


Fig. 2.10 :Loss of erosion pin during mass failure

Another disadvantage of the erosion pin technique is soil creep and surficial crack deepening with a pin embedded in the slump (Fig.2.11) leading to false readings.

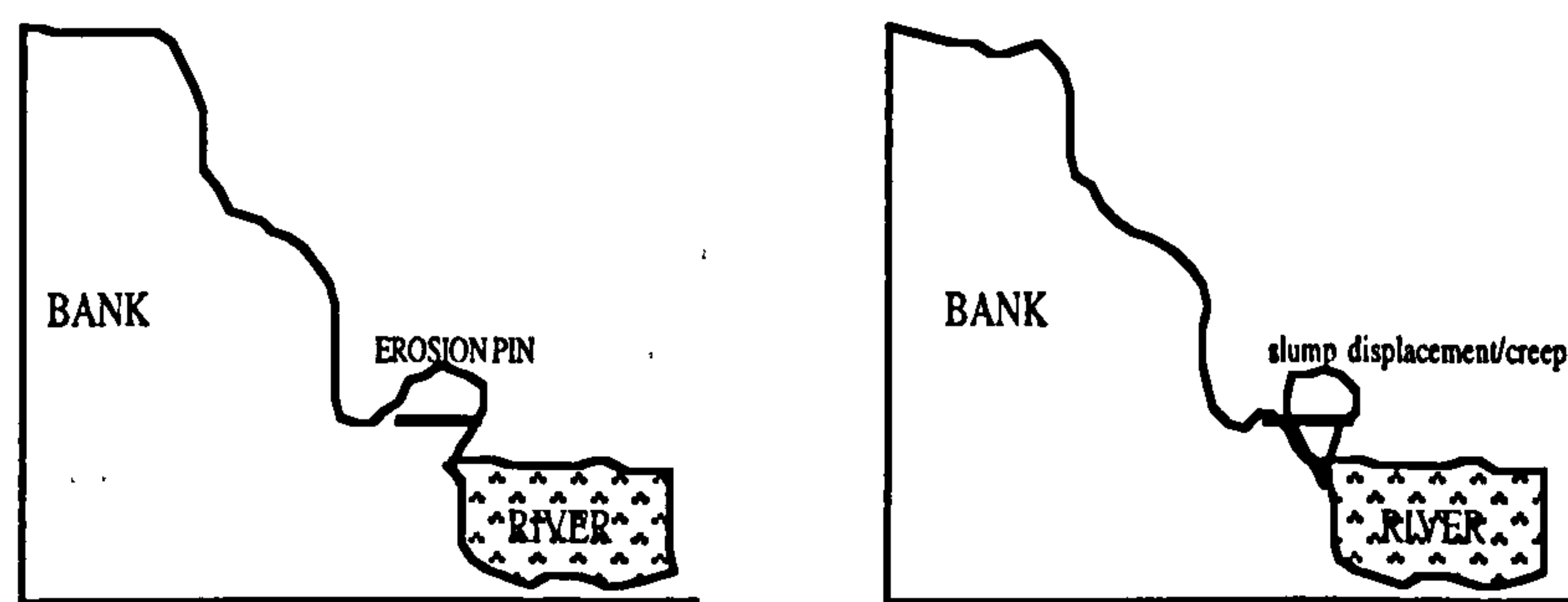


Fig. 2.11 : Slump displacement and associated error in pin technique

Measurement error for erosion pins: Haigh (1977) reviews the uses of erosion pins in the study of bank erosion. He identifies the following factors as of significance in the disagreement among researchers on the use of an erosion pin:

- i. the length and composition of the erosion pin;
- ii. the use of the washer;
- iii. the initial exposure allowed to the erosion pins;
- iv. the disposition of the erosion pins on the hill slopes;
- v. the time interval between data records;
- vi. the method of data recording.

He lists nine recommendations on the use of erosion pins. These have been assessed with respect to the suitability of the project and applied as relevant. In addition, Haigh (1977) discusses seven sources of 'data contamination' that can arise in using the erosion pin technique. Of these 'errors in recording' constitutes one category. In this study, all measurements were carried out using a millimetre marked ruler. Consistency of recording was ensured by measuring the underside of the pin protruding from the bank surface. The upper side was another alternative while a lateral measurement would have led to inability to a constant vertical positioning of the measuring ruler. A pre-experimental trial of 20 pins each of 40cm length was carried out on a denuded bank adjacent to the experimental area. Pins of random height of protrusion (of between between 0 to 15cm) from the ground were inserted at equi-distances of 10cm from each other along a horizontal axis, approximately 30cm above the ambient river flow level, in May 1986. Six consecutive readings were made from each pin at approximately one hour intervals. The limits of accuracy were $\pm 0.6\text{mm}$.

This is well within acceptable levels on the basis of Lawler's (1991) appraisal of this technique.

Summary of how the errors arising from the use of the pin technique were avoided or allowed for in this study

(1) avoidance of errors: as stated previously,

a. location of pins covered by vegetation Previous researchers (Hooke, 1977a) abandoned attempts due to the time consumed, and the difficulty of finding them when experimenting in a diverse range of streams on the same project). In this study,

(i) work was carried out in one continuous stretch of a straight river with a bank height of only upto 2.5 - 3m, a slope of 1.5:1 and a bank vegetation dominated by *U. dioica*, *E. hirsutum* and various grass species (see Plate 1 and Fig.2.3); These factors reduced the elements of site diversity and complexity.

(ii) a grid pattern of erosion pins (see Figs. 2.8a & 2.8b) with clear distances between pins within a plot frame of 5mX2.5m eliminated the otherwise problematical location of the pins if they were inserted in a non-grid or at worst, a random pattern.

(iii) at the apex of each plot above each vertical row of pins a permanent wooden "baseline marker" peg (9" long) driven to the ground, at 50cm above the apical pin position. From this peg, at each instance of recording erosion of the pins below, a white 'twine' string was dropped to the base of the plot (at the bank-toe). On this string were markers at 50cm intervals. This simple technique was effective in reducing the time spent in location of not only the pins in vegetated plots but also Bare banks. It was evident that this considerably reduced the 'trampling pressure' or disturbance of the bank vegetation that would otherwise be of significance.

(iv) the pin position was sprayed with a water resistant car paint (red) in an approximately 5cm diameter circle with the pin at the centre, a technique used by Thorne (1978) (see discussion earlier in 2.4.1);

(v) the pin head itself was capped with a red plastic head barely larger than the pin head itself (see discussion earlier in 2.4.1);

B. possible errors in measurement and how they were avoided discussed earlier (see 2.4.1, Measurement error for erosion pins);

(2) **allowance for errors:** experimental errors are almost universal. What is needed is to identify whether the experimental errors significantly contributed to the erroneous assesment/analysis of the results and the conclusions arrived at. In this study the main source of error would be those pins either presumed lost due to slumping or covered by vegetation (marked with the legend, X, in data records. Hooke (1977a, p202) states "The main problem at such sites (actively eroding meander bends) is that erosion is so rapid that even 80cm long pins were frequently lost through complete removal. ...

.....Longer pins would have been difficult to put in the banks. No evidence was found to substantiate the idea that partly eroded pins might be pulled out by the force of the water."

This work was limited to a straight reach of the river and flow intensities were less than those in the sites used by Hooke. However, records were made of pins lost due to slumping and thereby unable to locate at a particular period of erosion measurement. The following is a quantitative summary and an assesment of the percentage of pins that led to the error and therefore the possible in/significance of it to the final results.

Bare banks treatment			Normal Vegetation treatment			<i>Phalaris arundinacea</i> treatment			Nat. re-vegetation treatment		
month - year	X/T	% error	month - year	X/T	% error	month - year	X/T	% error	month - year	X/T	% error
Aug-86	2/54	3.70	No Lost pins			Aug-86	3/54	5.55	Aug-86	2/54	3.70
Sep-86	3/54	5.55				Sep-86	2/54	3.70	Sep-86	3/54	5.55
Dec-86	1/54	1.85									
Jan-88	3/168	1.78									

$X/T = (\text{number of pins not located, presumed lost due to slumping})/(\text{total pins in treatment})$

NB. Total number of pins per treatment = 54 i.e. 6 plots per treatment x 9 pins per plot upto March 1987 (see Figs. 2.8a & 2.8b) and 168 thereafter, i.e. 28 pins per plot.

2.5. Experimental data gathering periods:

Shear strength, moisture content and root density (total root length per unit volume of soil) were measured on a seasonal basis so that :

i) the expected flow levels during the given period would be low to allow gathering of data; However it was expected that during winter problems of saturated or submerged lower

banks from a fast running/ high flow river would be an obstacle. This has been the experience of previous authors.

ii) physiological and morphological changes of the bank vegetation arise due to the seasonal weather and hydrological changes. The root effects may be termed the rhizospheric as we deal with the area in proximity to the roots as that affected by root density or other properties. Similarly, shoot effects may be termed the phyllospheric effects.

iii) unacceptable levels of bank top-soil destruction through the sampling processes (experimental error) should not be allowed on the bank surface on any plots.

February, May, and August were chosen as the suitable months because:

February: the end of winter flooding with a subsequent low flow; This was expected to facilitate the measurement regime with the minimum damage to the banks that may arise from trampling.

May: the beginning of spring with much (above ground) plant growth activity under way ;

August: end of summer when (above ground) plant growth was at an end for the year.

2.6. Flow Regimes

Stream discharge data were supplied on request by the Anglian Water Authority (presently, the National Rivers Authority/Anglian Region) from their Willen weir river discharge recording station (Cotton Valley Sewage Station) situated approximately 700m down river from the experimental area.

Recordings are made on a daily basis. Measurements are carried out as the height of flow above a reference weir head. This reading is converted to discharge in litres per second.

Over the 25 months of the experimental study on this reach of the River Ouzel, three aspects of the flow are graphically presented.

They were : i) Minimum discharge ($l\ s^{-1}$); see : Fig.3.1a ;

ii) Maximum discharge ($l\ s^{-1}$); see : Fig.3.1a ;

and iii) Mean discharge ($l\ s^{-1}$); see : Fig.3.1b ;

of the river at this site for the periods between erosion measurements on the banks.

The main reason for limiting the study of different aspects of the flow to these three levels is because this study concentrates more on the effects of vegetation on bank stability

than on the effects of other diverse factors such as boundary shear stress or secondary isovels. Other authors such as Hooke (1977a &b) have delved deeper into the aspects of rise and fall of the hydrograph and precipitation with reference to eroding bare banks. This study attempts to incorporate the effects of the rise and fall of the hydrograph with the emphasis laid on a comparison between bare banks and banks with different types of vegetation, in an attempt to understand the erosive processes under the latter rather than the former. Special consideration for such factors as variations of ground temperature and incidence of frost are not considered as priorities for this study. However, field notes were made on frost incidence throughout the study period.

Reference will be made to Figures 3.1a and 3.1b which depict these three key aspects of the flow regime throughout the analysis to arrive at conclusions from the erosion graphs as and when relevant. As mentioned earlier flow was telemetrically controlled in this reach of the river. This ensured the validity of the records and explains any irregular flooding as shown in July 1987.

2.7. Regimes for analysis of erosion data

It is necessary to discuss the variations in rates of erosion in the experiments on the basis of the hydrographic changes of the reach of the river over the 25 months as discussed above. As such each graph on erosion is depicted under a graph of the mean daily flow for the corresponding period of erosion measurement (c.f. Fig. 3.3).

If the study was a survey of erosion as carried out by other authors, then the discussion can be limited to two periods (viz. : the highly erosive winter period associated with high flows and the non-erosive summer period associated with low flows). But as this study encompassed a series of experiments (as opposed to a survey), it has to address the processes of erosion at the initial periods of the experiments so as to understand the effects of experimentation on the bank. For example, in Experiment 1, the banks were artificially denuded and kept denuded throughout, while in Experiments 2 and 3 the initially denuded banks were allowed to re-vegetate by cultivation or natural re-vegetation respectively. In addition, the winter floods of 1987-88 were extremely severe in comparison with normal British winter flows. Taking all the above factors into account, it is considered best to interpret the magnitudes of erosion in the three experiments in five stages as follows :

- a) **Phase 1:** initial period of low flow (June to December 1986);
- b) **Phase 2 :** first period of winter erosion (December 1986 to April 1987);
- c) **Phase 3 :** first summer erosion within treatments(April to October 1987);
- d) **Phase 4 :** a winter of early storm flow of long duration (October 1987 to April 1988);
- e) **Phase 5 :** second summer erosion within treatments (April to August 1988).

2.8 Erosion Analysis

The analysis was carried out in keeping with the aims of each experiment. Having quantified erosion on the plots the next step was to condense them in such a way as to enable a valid comparison of the data through graphical presentation and statistical analysis so that correct conclusions could be reached.

Graphical Presentation: Initial graphical comparisons based on total amount of erosion per month or period of measurement were considered unrepresentative as the time interval between measurements were variable and comparison with the mean channel discharge per period would not be comparable. It was decided that the means of both erosion and discharge be based on a daily basis, calculated as the mean value for the period between consecutive sets of erosion measurements. This was more representative of the processes of erosion and channel discharge. As such all graphs are based on calculated mean erosion per day and mean discharge per day. This form of presentation (mm d^{-1}) is practised by other authors such as Lawler (1986).

One significant area of controversy could be the period of October 1977 to February 1988 when the 50cm level (level 1) from the base of the river was completely submerged in the unusually long flood of late 1987. The total time period between taking the measurements for this level was approximately 160 days (± 6 days for actual measurement period for all 24 plots).

Statistical analysis : is used where graphical comparisons present uncertainty on the significance of the differences between the two treatments either within an erosion period or within a 'Phase' as delineated above. The tests used are :

- i. z-tests (this is incorporated in Students' t-tests in software packages Statview 512+™ and Statworks™ used in this study) for individual comparisons within a period ;

ii. Analysis of Variance (1-way ANOVA) for testing the differences between treatments within a 'Phase' as defined in 2.7.; A 2-way Anova is used where there is a necessity to test for significant differences between treatments and between similar Phases (eg. winters of 1976/77 and 1977/78);

iii. Kendall correlation is used as a test of correlation between variables such as (a) mean or maximum flow and mean erosion for a phase.

2.9. Problems and weaknesses of the Methods used:

Much of the problems and weaknesses on the use of shear vane as an instrument for measuring bank shear strength, the techniques of moisture content measurements and root density, erosion pin technique, and cultivation of *P. arundinacea* from seeds on the banks, have been mentioned in 2.2. to 2.4.1 above. A discussion on the extent of the problems and weaknesses with special relevance to this study is necessary so that we may understand the overall impact of them to the reasearch findings.

(a) shear vane The use of the shear vane limits the depth, within the soil, to which it can be used as the maximum depth the vane can reach is 20cm from the surface of the soil. For this study the envisaged depth of bank shear strength variations was the uppermost layer that was between 0 to 15cm. However this limitation may have serious problems if future studies are intended on further depths.

The problem of non-uniform distribution of roots and the presence of the roots themselves is a drawback that can not be rectified at the present time. There is a lack of instruments that are more accurate and suitable for the field. These limitations have been discussed by other authors (Thorne, 1978; for river banks) and Gray (1974; for dry land slopes) who recommend the shear vane as the valid option for field measurements from within the available range of laboratory and field instruments. Later studies, Scholand et al.(1991), confirm the appropriateness of the shear vane under similar field experimental conditions.

(b) inability to measure shear strength of the banks during the process of active fluvial erosion This is a limitation arising from the inherent nature of the submergence of the banks. Even after the flow had returned to 'normal' ambience levels, the author experienced serious difficulties both in non-destructive measurements up the banks as well as inability to gain a

foot-hold on the slippery and saturated banks. The obvious alternative is to use a specially constructed adjustable platform which is moveable either within the channel or on the apex of the bank so that readings can be taken without undue destruction of the bank and ensuring personal safety. No other author has attempted this measurement during the process of intense fluvial activity due to the obvious limitations. Other reasons for allowing the banks to dry after incidents such as precipitation as opposed to flood incidents, have been discussed in 2.3.3 above.

(c) Rhizospheric measurements In this study, only total root length per unit volume of soil is undertaken. The reason for that is the conclusion from the literature survey, that previous work had been based on the study of root density and its influence on soil shear strength for dry land slopes. As much as the author would wish to question the validity of such studies, this experimental programme aimed to test the validity (of their finding for dry land slopes) in an alternative surrounding, i.e. wet bank slope.

From a plant biological aspect, it is an inappropriate assumption to expect a uniform distribution of roots of similar size within a rhizospheric area. The best results on uniformity in root density may be expected from a fibrous root system. A tap root system is associated with a diversity of secondary/lateral roots of various sizes, and a more vertical main (tap) root which may have other implications. For example it may have main aspects of anchorage of the plant. The fact that both shear strength measurements and root sampling were carried out in adjacent soil areas minimises if not negates the validity of any error for that bank area and depth.

If however, an intensive study is to be carried out on the rhizospheric effect on bank stability, as opposed to the phyllospheric effects, then a host of factors of theoretical importance would have to be addressed through a future programme. The main aspects of such a study should be the role of rootlets in soil cohesion, the process of root maturity and the physical changes in terms of tensile properties, the live/dead root turnover for different species under flooded and non-flooded conditions. As such, this study, while appreciating the holistic theoretical complexities from within plant biology, addresses the simplified findings of physical scientists (i.e. increase in shear strength of the soil with respect to an increase in root density alone). Such a simplification may be considered by some as a

weakness (and in fact 'theoretical reductionism' within a hypothesis). The author, while appreciating the possible criticisms would reiterate the fact that the first step is to test the validity of the findings of physical scientists for a dry land slope in terms of the relevance to a bank of a waterway, as is carried out here.

2.10 Rationale for the Survey:

The process of secondary succession of plants in a given habitat is associated with not only the establishment of new seedlings and propagules, but also the maturity of the established plants. The long-term establishment of monoclonal areas of plant species is dependent on the outcome of inter-specific competition and the realisation of the preferred niche of the species in terms of its survival within the resources of the habitat (Silvertown, 1981). Stress tolerance in terms of direct fluvial forces and short to long term submergence of these plants delineate the position each species will best colonise in the long term. While the experimental component of this study addressed the initial establishment of plant species either as cultivated (*P. arundinacea*) or as natural colonisers (naturally re-vegetated plots), there was a necessity to research into the variations of rooting patterns as reflected by the root density of long established colonies of *P. arundinacea* and two other main colonisers of the river bank, i.e. *U. dioica* and *E. hirsutum*. As previous authors (Endo and Tsuruta, 1968; Gray, 1974; Gray and Leiser, 1982; Waldron and Dakessian, 1982) co-relate increases of shear strength of mature monoclally vegetated soils to increases in root density, there was a necessity to attempt a survey of similar monoclonal vegetation patches. The parameters quantified were the same as for the previous authors, i.e. shear strength and moisture content of the soil and the root density. The apparatus used for the measurements were different. While the previous authors used other shearing devices such as the shear box (see 2.3.3) for shear strength measurements the hand shear vane was used in this survey. The validity of the use of this apparatus and the appropriateness of measuring total root length per unit volume of soil (as an alternative, technically relevant option when compared with mass of roots per unit volume of soil) are discussed in 2.3.3 and 2.3.5 (iii). Later work of Scholander et al (1991) confirms the author's views on the appropriateness of the techniques used.

CHAPTER 3

Experiment 1

A Comparison of Erosion under naturally vegetated and bare banks

3.1 Introduction

As elaborated in 2.1, this is a new approach to the study of bank erosion. Erosion has been studied for actively eroding banks under varying channel geometry, sinuosity, precipitation and flow conditions (Hooke, 1977a). Other aspects such as shear strength and moisture content in relation to the composition of the bank material of eroding bare banks have been investigated by Thorne (1978). Lateral erosion of long established vegetated and bare banks was quantified by Smith (1976).

This experiment is a development from the above studies leading to relationships between hydraulics, bank soil shear strength and natural bank vegetation in relation to bank erosion. The dominance of two species of vegetation, *Epilobium hirsutum* and *Urtica dioica* in the mid to upper regions of banks is identified. The main objectives are listed in 3.1.1 below as a consequence of the following thoughts.

a) *spatial demarcation of the bank based on wetness on a temporal basis* One of the most important factors is to quantify the variation in erodibility of the normally drier upper regions from the continuously wet toe-region of a stream. If wetness of a bank is associated with potential for slumping or corrasion then we have two spatial components of the bank that should be dealt with on a temporal basis.

i) The dry upper spatial component of the bank is wetted normally by precipitation or overland flows, while saturation by heavy precipitation and storm flows is seasonal. Both high precipitation and high flows are associated with winter in temperate countries while in a tropical country such as Sri Lanka it is associated with the two monsoon rain seasons of the year.

ii) The continuously wet lower spatial component (toe-region of the waterway) has a high moisture content throughout the year.

b) Presence of vegetation and the effects of roots on bank erodibility

Some of the first authors to comment on the effects of vegetation on channel bank stability were Mackin (1956), Hadley (1961), Brice (1964), and Zimmerman et al. (1967). An investigation in terms of the percentage volume of root in the bank and its effects on erodibility of the banks was carried out by Smith (1976).

There is a need to identify any relationships that exist between :

(a) erosion, (b) shear strength, and (c) root density, of a naturally vegetated bank as well as a bare bank.

c) undercutting of vegetated banks devoid of toe-region (semi-aquatic) plants

Intriguing processes of possible undercutting of banks at low flow levels are apparent under certain types of vegetation. The theory of undercutting at the basal region of grass dominated bank overhangs (Thorne, 1978; Thorne and Lewin, 1979), leads to certain questions. For example, can ambient flow at the basal region of the bank of a waterway be subjected to processes of minimal but continuous undercutting over long periods of flow, if there is no plant cover in this region ? It is also possible that certain temporary colonising species, especially on the basal region of the bank (Haslam, 1978), may be eroded themselves either at high flow velocities or during long periods of medium flow. Such erodibility of the plants (due to fluvial action) may create soil erosion where the plant was rooted. This phenomenon will presumably be related to the physical factors of root-soil cohesion and soil shearing resistance.

Therefore this experiment addresses a spectrum of problems hitherto suggested but not carried out by others.

3.1.1 Aims of the experiment

i. to quantify erosion on

(a) bare soil, and

(b) a naturally vegetated bank;

ii. to compare the respective rates of erosion for different flow regimes that occur through the period of experimentation (25 months);

- iii. to compare the rates of erosion at ambient flow under a naturally vegetated bank and a bare bank with special reference to the higher moisture toe-region corrosion;
 - iv. to compare the rates of erosion between the drier well vegetated upper region in naturally vegetated banks with the wet narrow band of the bank toe-region which was relatively vegetation free;
- (N.B. naturally vegetated banks on the experimental area of this river were remarkably low in amphibious 'toe-region coloniser' plants.)
- v. to study the variations if any, of the shear strength of the banks under the two treatments.
 - vi. to study the moisture content variations on the bank profile for the two treatments;
 - vii. to quantify the total root length per unit volume of soil on the bank profile for the two treatments; The bare soil treatment was not presumed to be free of live roots even though a systemic herbicide was used for de-vegetation;
 - viii. to evaluate any possible relationships between shear strength of the bank soil with moisture content and the total root length ratio (cm/cc) of bank soil;
 - ix. to identify any relationships between either of the above three factors singly and the prevalent discharge of water in the river ;

3.2. Some possible complexities in techniques and analysis

As moisture content and shear strength of the soil are inter-related (Ohu et al,1976), and root area ratio is related to the shear strength of the soil (Waldron,1977), it was considered that quantifying factors (a), (b), (c) and (d) in 2.1. (see Ch.2) would be useful in identifying the inter-relationships between the factors. Ideally one would be in a position to analyse the data in a multiple regression analysis where erosion would be the dependant factor which will be influenced by the three independent factors of shear strength, moisture content and total root length per unit volume of soil. Such an approach would lead to the possible evaluation of mathematical models for predictions of stability and erodibility. Ayers (1987) presents an attempt at the development of multiple linear regression equations developed to describe the soil strength-properties relationship for

different soil types. He discusses the obvious limitations of these equations and the high coefficients of variation even within soils of varying clay content.

The main problem is that sound theoretical predictive models may be beset with problems in laboratory studies, and field experiments or surveys. For example, variations inherent in soil composition characteristics and species diversity within the plots have to be accounted for in predictive models. As Kassif and Kopelovitz (1968) comment on the work of Kaul (1965), even though the latter found that the presence of roots increased the shearing and tensile strength of the soil at all moisture levels, the increase in strength was not the same when similar samples were tested as replicates. This was due to 'too many factors which could not be controlled during testing and hence could not be separated during the analysis of the results'. If such were the difficulties in interpretations on root effects of one species of plants grown under controlled conditions of a growth chamber, one has to understand the limitations associated with simulating either long-term established, naturally vegetated banks or the simulation of temporary basal coloniser species under a three year field or laboratory experimental regime. Therefore this study is limited to addressing the fundamental relationships and patterns between and within the main parameters quantified (see 3.5.1) rather than the development of accurate predictive models.

On the other hand, if a comparison is made of the rates of increase of shear strength imparted by different species of plants on different soils as shown in the classical diagrams of Gray (1978), then it appears that the accuracy of the apparatus measuring the shear strength, and the total root length of the rooted soil is important. In this study the quantification of shear strength of the soil, root length per unit volume of soil and bank erosion have been carried out with reasonable accuracy (see Apps. 5a, 5b, 5c, and 6). The use of a hand shear vane to measure the shear strength of the vegetated soils may be considered controversial with regard to accuracy and appropriateness. However the reasons for its usage were given in 2.3.3.

As discussed in 2.3.1 (in Ch.2), the large size of the experimental plots and the search for broad trends in comparisons between treatments, in long-term field

experiments are expected to over-ride the individual accuracy sought in intensive, small-scale, short-term laboratory experiments. This is accepted practice by field scientists (cf. De Wit, 1960; Yoda et al. (1963) who base universally applicable predictive models on such trends. For example Yoda et al (1963) developed the universally accepted self-thinning law in plant population ecology, based on data under both cultivated and natural conditions.

As the focus of research is on the aspects of erosion of banks, relevant to the Regime Theory the mode of analysis of erosion data on the experimental area was to be carried out in two ways as shown in 3.5.2. and 3.5.3. below.

3.3. Materials and methods

Site Description : This has been presented in 2.2.1.

Experimental Plots : 1a, 1b, 7a, 7b, 12a, 12b were the devegetated plots known as the Bare Bank Treatment; 3a, 3b, 6a, 6b, 14a, 14b were the naturally vegetated banks sometimes referred to as Normal Vegetation Treatment. Both are as shown in Figure 2.3. The technique used for devegetation and the frequency of it has been described in 2.3.2.

Apparatus Used: refer to 2.3. to 2.4.1.

Methods : as described in 2.3.2 to 2.4.1.

3.4 Results and Analysis of Data:

3.4.1 Results:

The results consisted of five main sets of recordings. They were:

- a) Erosion measurements over 25 months; time intervals of recordings are in Section 2.5; (see Appendix 2 and 3 for erosion data on banks)
- b) Shear Strength measurements (kPa); (see Appendix 4);
- c) Moisture Content measurements (percentage) (see Appendix 4);
- d) Root length ratio measurements (cm/cc); (see Appendix 5);
- e) Daily hydraulic discharge near the site ($l\ s^{-1}$) (see Figs. 3.1a and 3.1b for mean daily flow and Appendix 2);

(summarised data as used in the analysis are presented in the Appendix)

3.4.2 Erosion Analysis:

The analysis was carried out in keeping with the aims of the experiment as set out in 3.1.1.above. (see 2.8)

Statistical analysis (see 2.8)

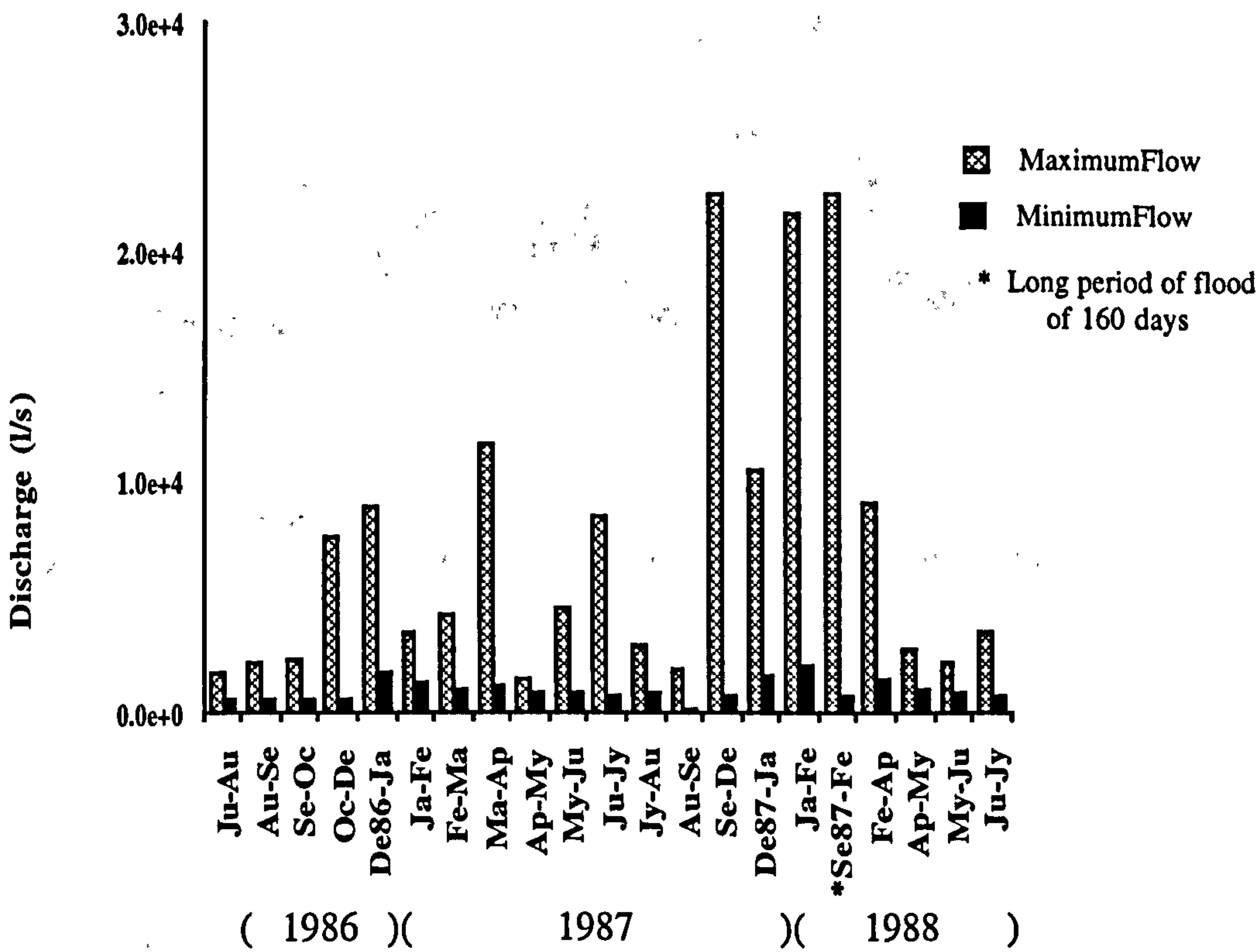
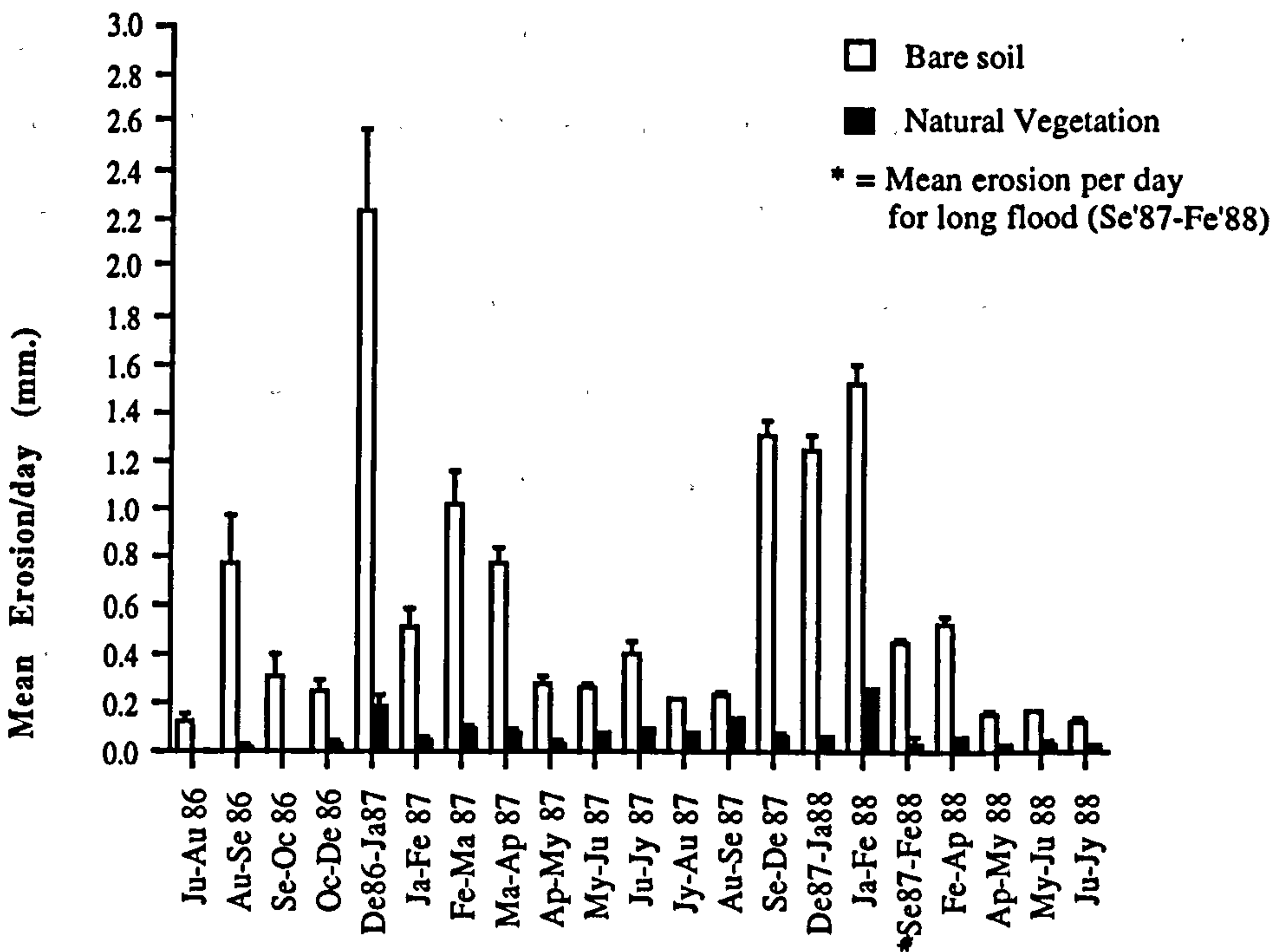
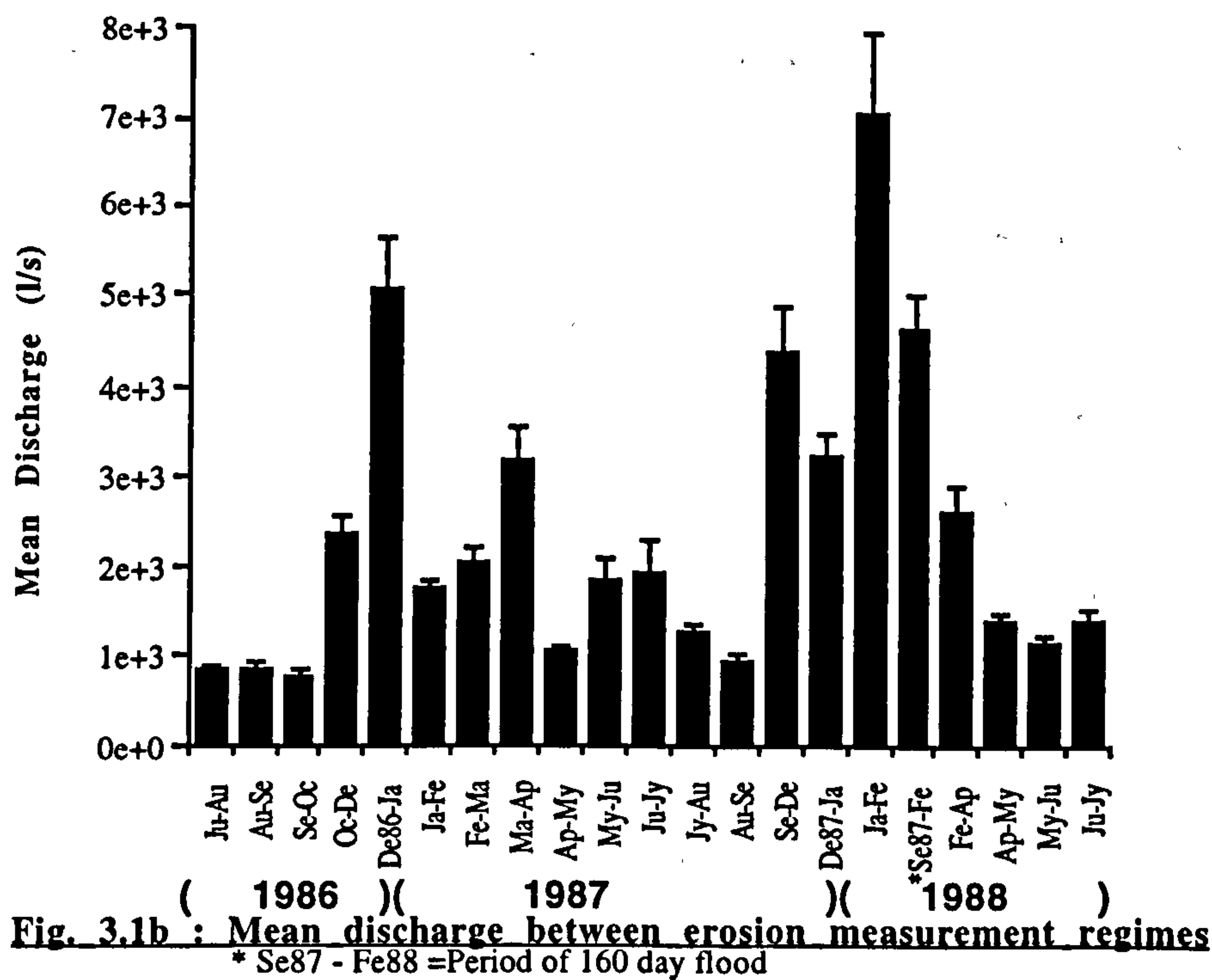


Fig. 3.1a : Maximum and minimum discharge during period of erosion.

N.B. The highest flow for the period of September 1987 to February 1988 is depicted above in addition to the highest flow variations between September 1987 and February 1988. It is observed that the former coincides with the highest flow recorded in September to December 1987. The particular date was 21st October 1987.

3.4.2a Comparison of erosion of Bare soil versus Naturally Vegetated Banks (whole banks)



(six plots per treatment; mean erosion per day = average of recorded erosion of six plots (128 pin readings) / No. of days in erosion period; Error bars = Standard Error)

Some comments on the individual behaviour of each treatment

Before discussing the comparative performance between the treatments it is best to discuss the behaviour of each treatment during the experimental regime (see Fig. 3.2).

a) Bare Bank Erosion : June to August 1986, which was the initial period following the positioning of erosion pins and the application of systemic herbicide, indicates low flow and relatively low erosion . Field observations for the same period on the geomorphic appearance of the denuded plots showed medium sized surficial cracks appearing in the mid-region of the banks (Levels 2-3; see Fig.2.7 where levels are shown). There were some positions that had initiated the process of 'cracking up' of the dry exposed bare banks. This was somewhat similar to the common occurrence of cracking up of dried exposed canal beds during a drought.

August to September 1986 shows the highest rate of erosion per day noticed for a low flow level during the period of experimentation. On analysis of the data at the completion of the study it was obvious that the highest rate of erosion under sub-bankfull and bankfull discharge is during the first few months following denudation by a systemic herbicide. Plate 3 shows that the lower to mid-bank region had eroded with the first sub-bankfull flow leading to consequent instability of the mid-bank overhang (see left edge of Plate 3). It was observed that these overhangs were held to the main bank by the dead roots. Consequently these dry-banks slump even in the absence of wetting of banks. The conclusion is that these overhangs were temporarily prevented from erosion (slumping) by the tensile properties of the dead roots that bound it to the main bank. Tensional failure and the development of desiccation cracks between a cantilever block and the bank face are discussed in depth by Thorne (1978, pp.90-120).

October to December 1986 flood was the first high flow consequent to denudation. It shows an initial high rate of erosion for bankfull discharge. But it was during the December 1986 to January 1987 stormflow that we notice a higher rate of erosion. The following are presented as the reasons for the delay in the magnitude of erosion initially :

i) the maximum discharge for October to December 1986 was c.7500 l s⁻¹ but the mean discharge was c. 2500 l s⁻¹. The maximum discharge for December 1986 to January 1987 was c. 8500 l s⁻¹, with a mean discharge of 5000 l s⁻¹. Even though the maximum discharges were not very different, the mean discharges for the period were significantly different. Therefore at this stage of experimentation the duration of the high flow is a significant factor in bank erodibility.

A statistical analysis (Kendall correlation) confirmed that :

a) for the whole experimental period correlation between mean flow rates and mean erosion per day is high (statistic : 0.495; significance : 0.001) ;

b) for the winter periods of December to April 1986/87 and 1987/88 correlation between mean flow rates and mean erosion per day is not significant at < 5% level (statistic 0.071 and significance 0.402);

c) for the winter periods of December to April 1986/87 and 1987/88 correlation between maximum flow rates and mean erosion per day is not significant at < 5% level (statistic 0.202; significance 0.209);

ii) the presence of dead roots left in the bank soil as a result of denudation by the systemic herbicide, prevented a high erosion in the first stormflow;

iii) the roots underwent a process of 'loosening up and decay' during and soon after the first bankful discharge. A reasonable hypothesis is that the application of systemic herbicide and the death of shoots and roots led to the following phenomena:

a) created a soil structure that had less bulk density (see Bulk density values in Appendix 9), due to air spaces being formed in the dead and decaying root cavities in the soil; (Tenbeigh, pers. comm.) confirmed a similar loss of bulk density and shear strength in his laboratory studies but had not tested the root exudate binding aspects as a possibility.

b) loss of cohesion factor (C₂), (2.3.5.) previously imparted by the live root exudates in binding the roots to the soil.

c) more porosity of the soil, leading to increased erodibility ;



Plate 3. Bare bank in September 1986 (Plot 1b)

N.B. Lower & mid-bank failure after denudation with fast re-vegetating patches which needed spot herbicide application

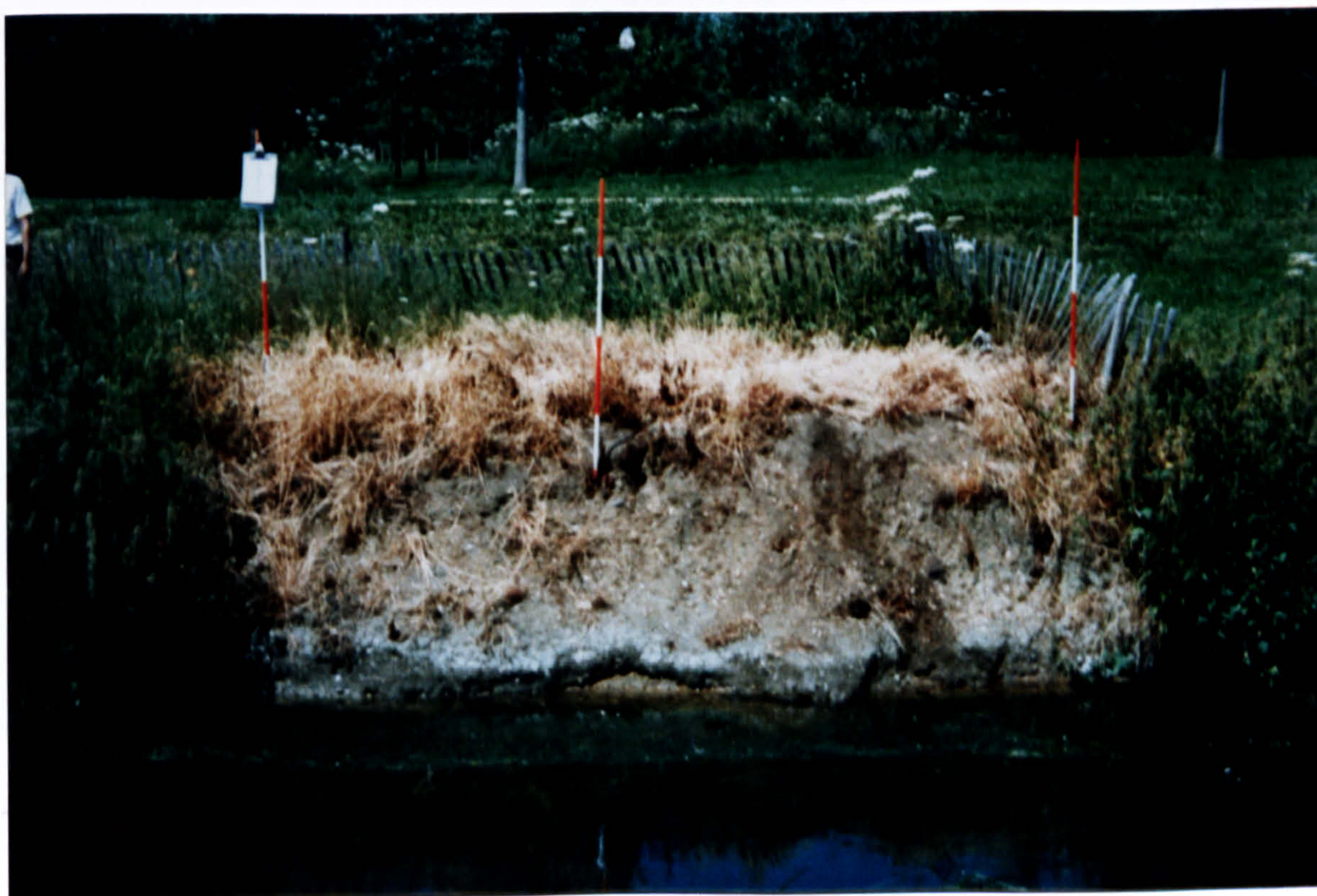


Plate 4. Bare bank in August 1988 (Plot 1b)

N.B. bulk of the bank had been eroded in the floods of 1987/88

iv) this delayed erosion agrees with the process of pre-conditioning of the bank in the first flow by saturation, followed by wet bank slumping and increased erosion in the next high flow as noticed by other authors such as Hooke (1977a);

It is worth comparing the two winter erosion rates associated with floods during the period of experimentation (September 1986 to February 1987 and September 1987 to February 1988).

Seasonal Mean erosion : Summer erosion is low as expected. May to September 1987 shows low erosion similar to that of May to July 1988.

Winter erosion (see Table 2 /p 121) under Bare banks appear to have two patterns of mean erosion per day for the two successive years of 1986/87 and in 1987/88. The explanation lies in the two vastly different patterns of inundation of the channel during the two winters. While the 1986/87 initial floods (Sep-Oct and Oct-Dec) were consistent with normal pre-winter flow patterns, that of 1987/88 were drastically severe. As such in 1986/87 winter the first floods prepared (wetted) the banks for erosion by the ensuing high flows in December to January as discussed in (iv) above. In contrast, the flow pattern in the winter of 1987/88 was one of a severe onslaught of floods on the exposed banks by the 08th of October followed a long term telemetrically controlled flow in this stretch of the river. Bankfull flow was maintained throughout.

b) Naturally Vegetated Banks : On the whole erosion rates were low during both summers (Fig. 3.2). In this study, summer erosion associated with ambient flow regimes under actively growing vegetation is discussed mainly with reference to lower bank erosion in the toe-region (see 3.5.2b). What would be significant is any cumulative erosional effects which may indicate bank instability.



Plate 5. Natural vegetation dominated by *Epilobium hirsutum* (Plot 3a)
 N.B. Lack of fringe vegetation (at level 1) thereby exposing this area to undercutting



Plate 6. Natural vegetation dominated by *Urtica dioica* (Plot 5a)
 N.B. Lack of fringe vegetation (at level 1) thereby exposing this area to undercutting

3.4.2a Variations of erosion within and between Bare-soil banks and Naturally vegetated banks

Phase 1 : initiation of bank destability and erosion under ambient flow regimes; (see Fig. 3.2; June to December 1986)

Even at ambient flow regimes the initial processes of top-soil destabilisation and erosion by weathering of the banks and possibly the death of roots in the banks, occurs as a highly significant process. Within this stage the rates of erosion increase to a maximum within the first three to four months (June to September 1986 in Fig.3.2). Thereupon the rate of mean erosion of the bank declines almost linearly over the next three months until the first period of high flow (Stage 2) within the channel occurs. The reasons for a steep decline in erosion are : (a) over the first four months the de-stabilized soil mantle has been eroded; (b) the soil exposed as top-soil by the fifth month has a higher bulk density and shear strength and hence minimal erodibility. Any discrepancies that may arise due to erosion of the upper bank and possible accretion at the lower banks at ambient flow regimes will be addressed in 3.4.2d and 3.4.2e.

Phase 2 : Erosion during the first winter period of high flows (December 1986 to April 1987) : The bare banks undergo the highest rate of erosion during this period, as pointed out earlier. For the naturally vegetated banks it is not the highest period of erosion. In fact it is the more severe second winter (1987/88) which is the higher erosive period for the latter treatment. This is to be expected due to the magnitudes and lengths of periods of storm flow during that period.

Phase 3 : For experiment 1 the first summer of April to September 1987 is not associated with any growth of new vegetation in the bare banks. As such the erosion of bare banks continues. The high erosion rates from April to September 1987 are associated with the changes of the hydrograph during this summer (Fig.3.2). The contributory factors to this are (a) erosion (slumping and corrosion) at high flows; (b) erosion (wet bank slumping) soon after a high flow and (c) cycles of weathering (drying of top soil combined with wind blowing) and wetting in sequence.

Phase 4 : Erosion during an early winter storm flow of high magnitudes and long duration : The onset of the sudden change of weather in the first week of September 1987 followed by the unprecedented severity of precipitation and storm flows caused a high, continuous period of erosion of the bare banks.

The naturally vegetated banks did not erode to any comparable levels of increase in the first five months (September 1986 to January 1988) as shown in Fig. 3.2. But the highest storm flow that occurred in January to February 1988 together with the highest mean daily flow through this period is associated with the highest rate of mean erosion under naturally vegetated banks. The explanation is twofold. Firstly, the low erosion in the first storm flows is due to the presence of healthy vigourously grown vegetation on the banks by September 1987. Normally temperate plants commence the process of death and loss of foliage later than September. The effect of the presence of healthy foliage was the reduction of erosion arising both from high precipitation and the lateral force of the channel flow. The foliage acted as the intermediate barrier as suggested in 1.2.2. If the foliage was absent as in normal winter erosion (compare with December 1986 to March 1987) then even under normal winter storm flow conditions there would be a higher erosion under naturally vegetated banks. The presence of foliage in September 1987 reduced the erosion process until they commenced the decaying process under submerged conditions (see Plates 14 & 15). This combined with a very high flow in January 1988 resulted in the highest rate of erosion under naturally vegetated banks. It is hence a process of 'delayed erosion'.

It is relevant to point out that the magnitude of erosion of naturally vegetated banks may have been much higher at the onset of the major floods if it occurred in mid-winter. What is more significant is the relevance of the above discussed 'delayed erosion' due to the presence of bank vegetation in the tropical countries. As these are mostly evergreens the implications are that naturally vegetated banks should act as a much better intermediary between the erosive forces of flood waters and the channel bank. Hence the channel regime will be subject to the type of plants (deciduous or evergreen) present on the banks.

Phase 5 : the second summer (April to August 1988) is associated with the continuation of the process of bare bank erosion associated with low flow levels and weathering conditions. The naturally vegetated banks show extremely low rates of erosion during this period.

Conclusions

1. The application of a systemic herbicide on the natural vegetation of a stable bank during summer is followed by three phenomena of erosive and hence geomorphic significance. They occur in the absence of motive fluvial forces:

(i.) the initial phenomenon of death of the vegetation (shoots and roots) associated with a "loosening up process of the bank soil mantle; the defoliation is itself associated with a process of flattening of the dead vegetation onto the ground and the removal of some of the debris by wind; some exposure of the bank to weathering.

(ii). the second phenomenon is that of a period of accelerated erosion of the mid to upper bank; in this experiment, the artificial removal of some of the dead vegetation has induced this process prematurely;

(iii). the third phenomenon is that of consolidation of the lower (root free) layers; this inference is deduced from the drastic reduction of observed erosion rates;

2. The absence of any intermediate barrier (natural barrier is vegetation) between the (mainly winter) high flows and the exposed bank soil is associated with the highest rates of bank erosion (see 1.2.2 and 1.2.3 in building a hypothesis and a possible model);

3. A long term flood (winter 1987/88) is associated with accelerated decay of the natural bank vegetation at later stages, leading to high rates of erosion in naturally vegetated banks.

4. A long term flood is not associated with complete death of bank vegetation; this conclusion is based on the observations of regrowth of the same vegetation during the following summer.

3.4.2.b Comparison of erosion of the lower banks when (a) covered with Natural Vegetation (b) exposed as bare soil

(Lower bank = 0.75m from the base = Level 1 in Fig 2.7)

The importance of the stability of the toe-region of a river bank arises mainly from findings of previous authors as discussed in 1.3. Knighton's description of bank erosion as a pseudo-cyclic process where undercutting is the first step in the process of erosion made it imperative that the above comparison be made in this study. Furthermore, in the first survey along the river bank while demarcating the plots for the experiments, numerous points of a concave soil profile were noticed under the ambient water level below the banks dominated by *E. hirsutum* and *U. dioica*.. This field observation together with the theoretical argument (see 3.1) leads to a question of whether undercutting of the toe-region is a continuous process in this reach of the river even under perennial vegetation such as *E. hirsutum* and *U. dioica*..

However one factor complicated a direct comparison of toe-region erosion under certain types of vegetation against a treatment of no vegetation. That was the continuous process of debris accumulation at the toe-region of the bare banks from the eroding and weathering exposed upper banks (Fig. 2.9) during ambient flow regimes. This was followed by the process of washing away of the built up debris by the next high flow. The original bank-surface was exposed to fluvial erosion only after the first process of wash away of the debris.

Under ambient flow in summer this river was flowing at approximately 0.5m from the bank toe; as such the erosion pins were positioned at this height for Level 1 (see Fig. 2.7.) so as to indicate any erosive processes at this level.

Figure 3.3 shows a clear difference between the rates of erosion even under summer flow regimes. i.e. April to September 1987 and April to July 1988. The magnitude of such erosion is much less than for similar erosive periods calculated for whole banks. But as Table 2 shows the cumulative amounts of erosion at the toe-region under the existing natural vegetation is noticeably high.

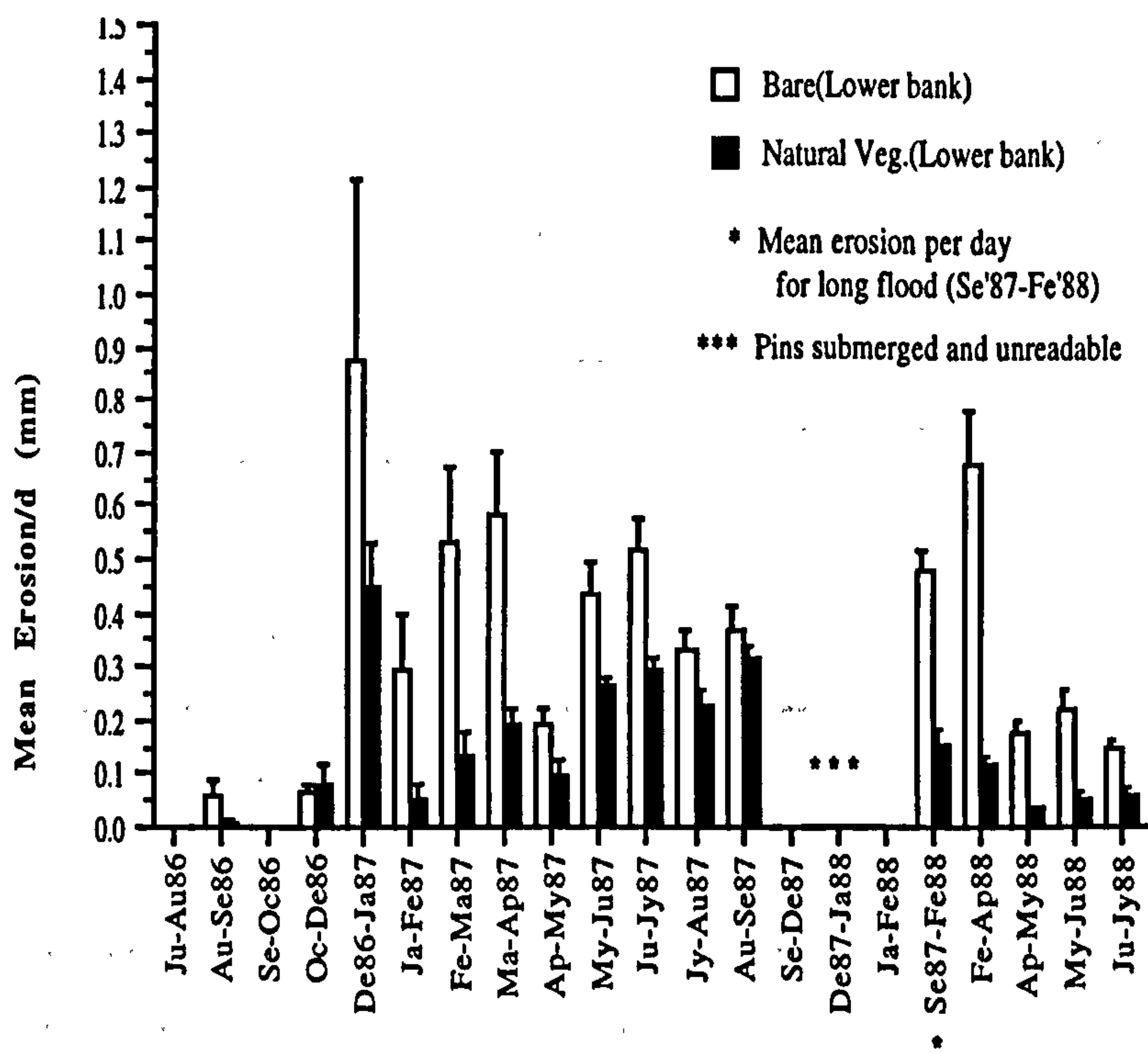
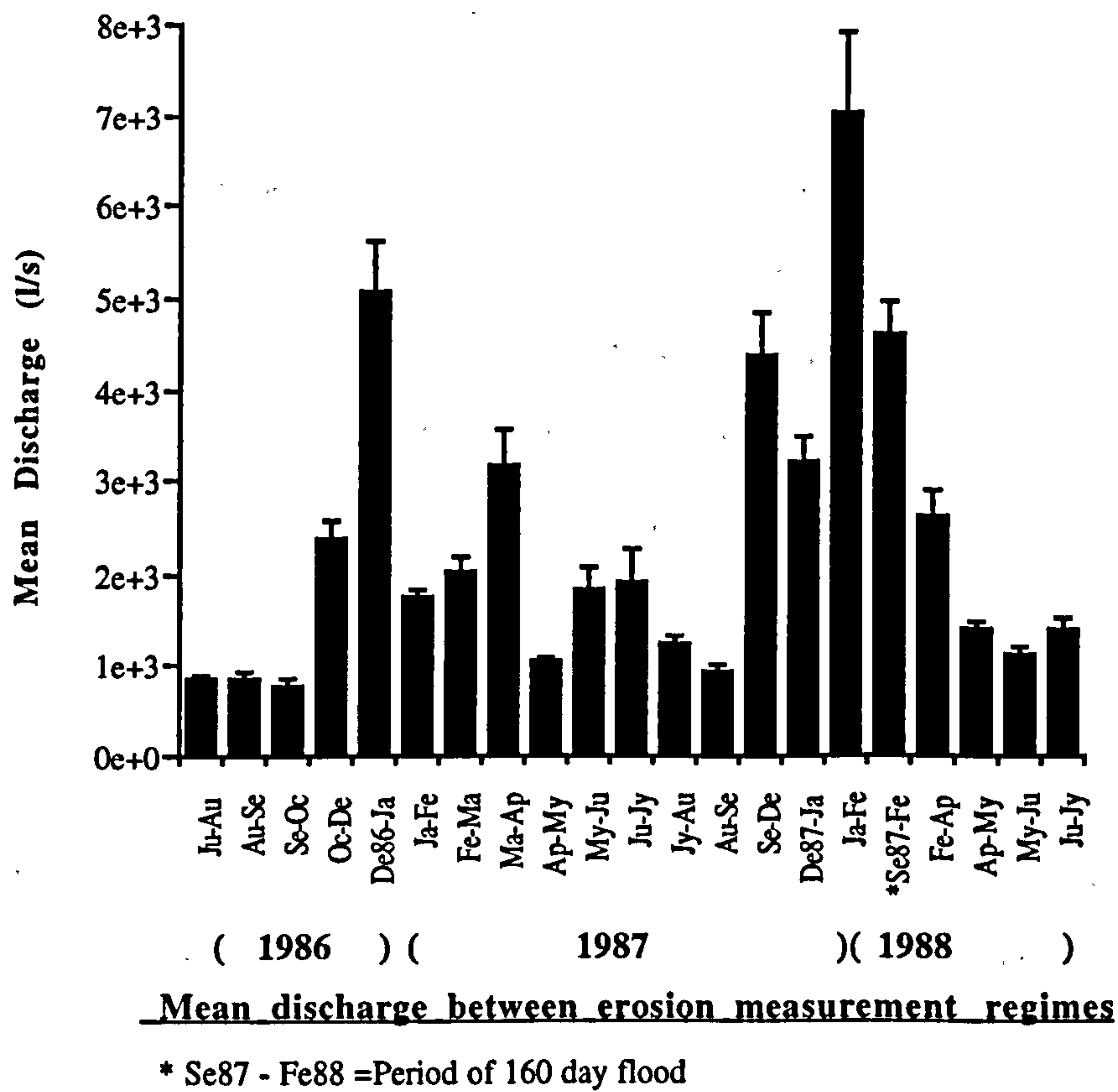


Fig. 3.3. : Comparison of Erosion : Bare soil Vs. Natural Vegetation;
(Lower banks)

However it may not be the true erosion or erodibility of the toe-region due to possible accumulation of debris falling from above (see Fig.2.9). For example, compare mean erosion per plot of bare banks for July to September 1986 with that for the lower bank of the same. There is significant erosion recorded for the whole bank but comparatively less erosion recorded for the toe-region (see Figs. 3.2 and 3.3).

For December 1986 to January 1987 following the first flood of winter of 1986 there is high mean erosion for the whole bank as well as the toe region of recently devegetated banks (Figs.3.2. and 3.3). The process of toe-region erosion for naturally vegetated banks is the true erosion as there was no debris accumulation from soil erosion above. For the bare banks this shows the erosion of the bank from the original pin position prior to being covered with the falling debris. In fact, the true amount eroded from pin positions covered with debris should include the depth of the debris washed away in addition to the erosion shown by the pin.

On the whole, during the experimental period, the correlation between maximum flow and mean daily erosion at the bank-toe for vegetated banks is not highly significant (Kendall correlation statistic 0.147 and significance 0.18; see Table 1a). The magnitudes of the rates of mean erosion for bare banks and vegetated banks appear graphically different (Fig.3.3). But in comparison with whole bank erosion under storm flows the magnitudes are minimal.

		Paired Observations	Statistic	Significance
For mean flow	Bare	21	0.312	0.026 *
	Naturally vegetated	21	0.176	0.137
For maximum flow	Bare	21	0.206	0.100
	Naturally vegetated	21	0.147	0.180

Table 1a Correlation analysis for mean erosion per day for the bank-toe region for mean and maximum flows between erosion measurement intervals during the experimental period

		Paired Observations	Statistic	Significance
For mean flow	Bare	21	0.390	0.007 *
	Naturally vegetated	21	0.360	0.011 *
For maximum flow	Bare	21	0.364	0.011 *
	Naturally vegetated	21	0.269	0.045 *

Table 1b Correlation analysis for mean erosion per day for the upper-bank region for mean and maximum flows between erosion measurement intervals during the experimental period

*** = staistically significant at <0.05%.**

3.4.2c Comparison of erosion of Bare soil banks versus Naturally

Vegetated banks (Upper banks = 0.75 to 2.5m upwards from bank-toe)

Upper bank erosion is expected to occur due to the following phenomena :

- i) continuous undercutting of the lower bank followed by upper bank slumping leading to removal of failed blocks (Knighton, 1984);**
- ii) direct corrasion as a result of high or storm flows.**
- iii) surface runoff as a result of precipitation;**
- iv) rotational slips (this phenomenon did not occur in this study area and as stated earlier will not be within this research discussion);**
- iv) wet bank slumping consequent to a high flow (Hooke,1977a &b).**

As shown in Fig.3.4 below, there is minimal if any, erosion for normally vegetated banks throughout.the experimental period. This includes periods of stormflow lasting for over three months. But the magnitude of erosion of the bare upper banks is highly significant. The level of significance in the comparison between the treatments is graphically obvious and at no period of erosion warrants a statistical analysis for confirmation. However as Table 1b shows, the flow correlation (both maximum and mean) with mean erosion is significant for both treatments in the upper bank region.

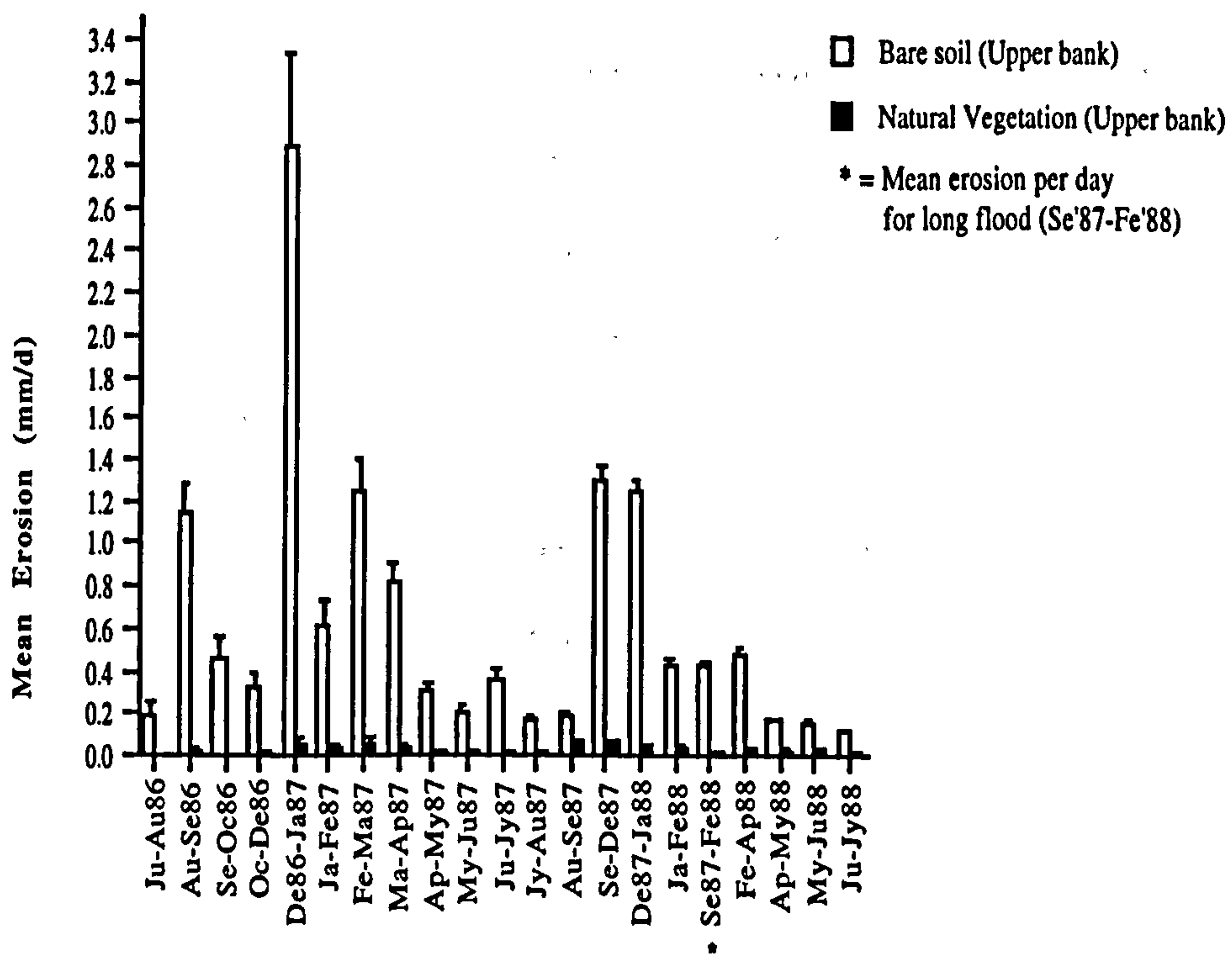
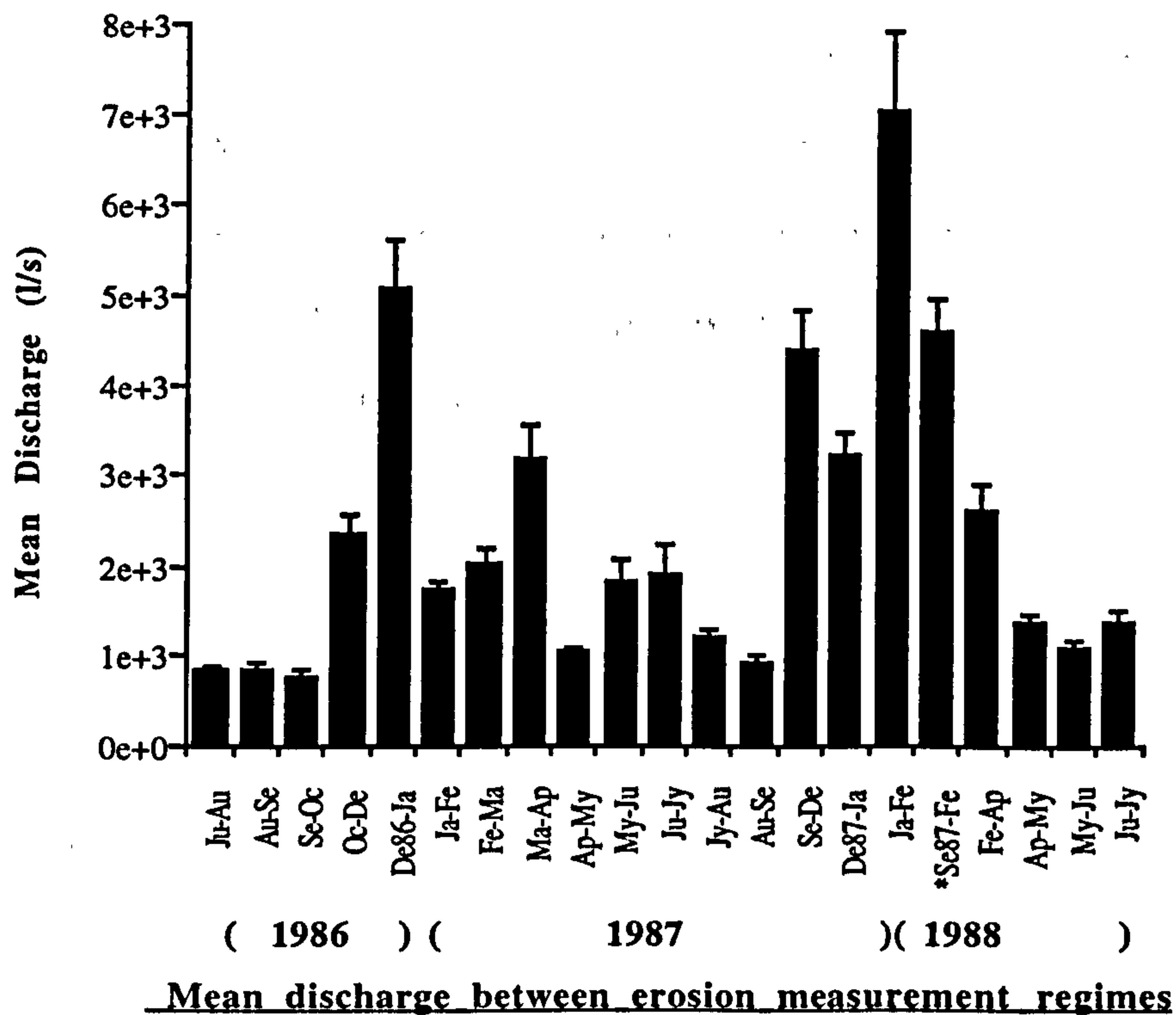


Fig. 3.4. : Comparison of erosion : Bare Vs. Natural vegetation; (Upper banks)

One particular factor of importance is that even though there were hardly any leaves on the bank vegetation, except the grasses, in winter (when most bankfull discharges occurred) there was a thick matting of dead, leafless stems and branches of the plants which formed a barrier of 'sieves' that may have prevented the potential erosive force of the stormflow from eroding the banks (see Plates 14 & 15). This aspect has not been researched into so far.

Even if there is a significant factor of safety created by the roots of the plants (for example, correlation between root length present in the soil with variations of shear strength of the soil, see 3.5.4 and 6.5), the probable importance of this dead vegetation cover in prevention of erosion during winter periods (as the intermediate component of the model proposed in 1.2.3) has to be taken into account.

Phase 1: initiation of upper-bank instability and erosion under ambient flow regimes (see Fig. 3.4; June to December 1986)

The comments made for comparisons of whole banks (see 3.5.2a) apply for the upper bank behaviour as well. Erosion rates increase to a maximum by September 1986 and decline rapidly until the first winter storm flow takes its effect (see Fig. 3.4). If comparisons of erosion of whole banks (Fig. 3.2), lower banks (Fig. 3.3) and upper banks (Fig. 3.4) are made it is apparent that the main contributor to the erosion is the bare upper bank during stage 1 where slumping was the result of denudation.

Phase 2 : Erosion during the first winter period of high flows (December 1986 to April 1987) In Fig. 3.4 the potential erosive effects created by denudation of a naturally vegetated bank are amply shown. There is no need for any statistical analysis to account for the significant difference between the two treatments. What is obvious is the very high initial erosion (when compared with the erosion rates for the second winter) of the upper banks during the first floods of the first (1986/87) winter.

Phases 3, 4 and 5 : all show the highly erosive nature of the upper region of bare banks in comparison with the highly non-erosive nature of the naturally vegetated banks.

There is no necessity to carry out any significance tests for identifying the differences in erodibility between the treatments. Reference may be made to Table 2 and 3.4.2f for further quantitative data and discussion.

Conclusion: Upper bank erosion is highly significant in a newly de-vegetated bank. If there is no natural re-vegetation or if the riparian/land owner maintains the banks as exposed bare soil then the process over the first two years is (a) initial destability of the bank top soil attributed to the death of the roots, followed by (b) wash away of the debris followed by high rates of top soil erosion under summer and winter flows.

3.4.2d Comparison of erosion within Bare banks (Upper versus Lower bank) (Fig. 3.5)

This comparison studies the process of erosion broadly on the basis of work done by previous authors on river banks with special reference to the pseudo-cyclic nature of erosion proposed by Knighton (1984).

Phase 1 (June 1986 to December 1986): Initial erosion following denudation is much larger in the drier upper region than the wetter lower toe region in the first four months which are characterised by low ambient flow regimes (June to October 1986). While for the upper banks the erosion rates increase to a maximum and then decrease, the lower bank behaves differently. There is hardly any erosion of the toe-region. Debris aggradation from above may have contributed to low erosion measurements in the toe-region as discussed earlier. The first high flow of October to December 1986 did not show an increased rate of erosion. By then the top soil had been eroded. This top soil contained a thick layer of ramified network of dead and decaying roots. As with most plants it is the top soil which contains the highest density of roots (Bohm, 1979). The application of the systemic herbicide possibly created a topsoil which was lower in bulk density. The bank soil exposed, following the erosion of the top soil, for the first high flow was observed to have less dead roots.

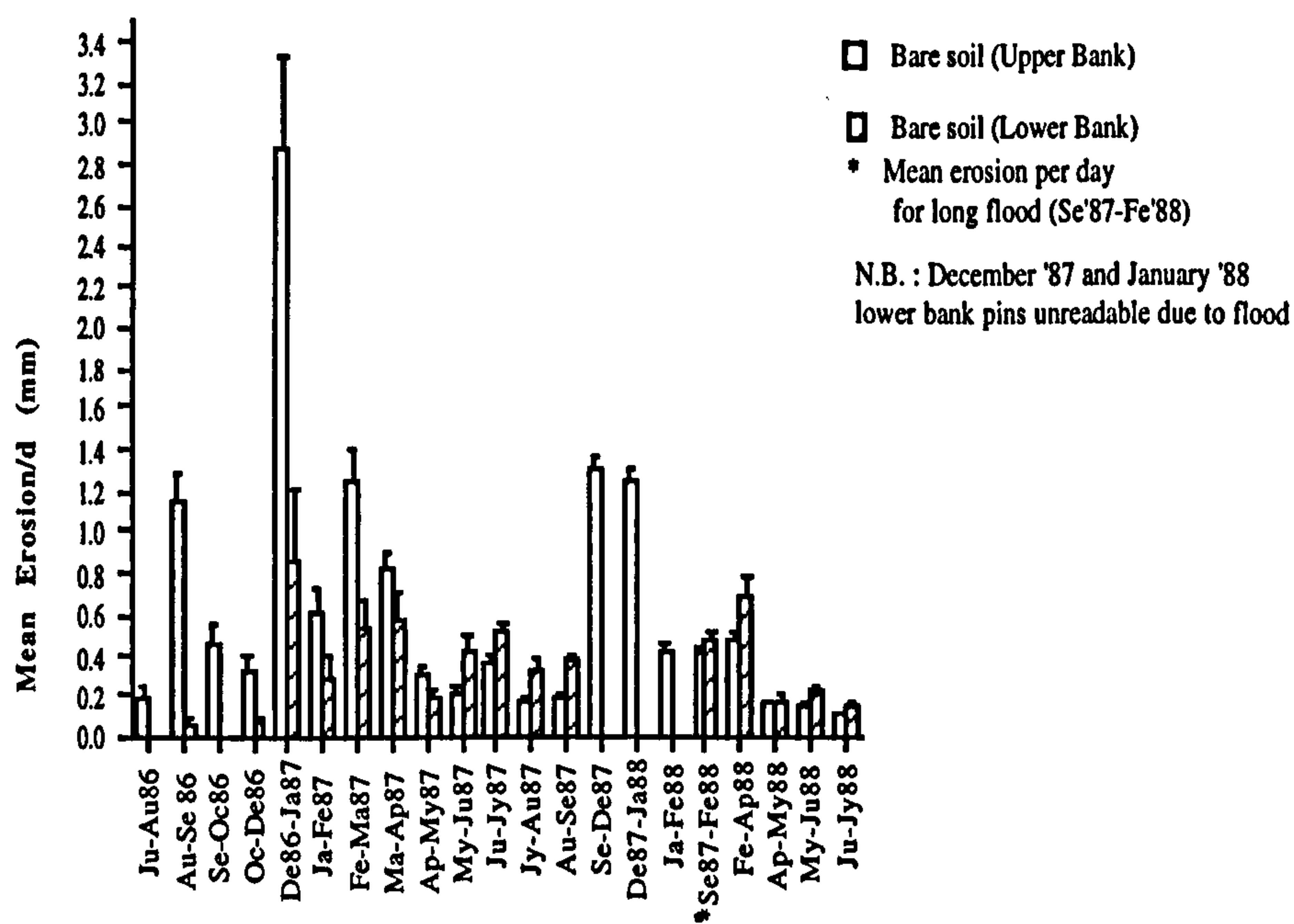
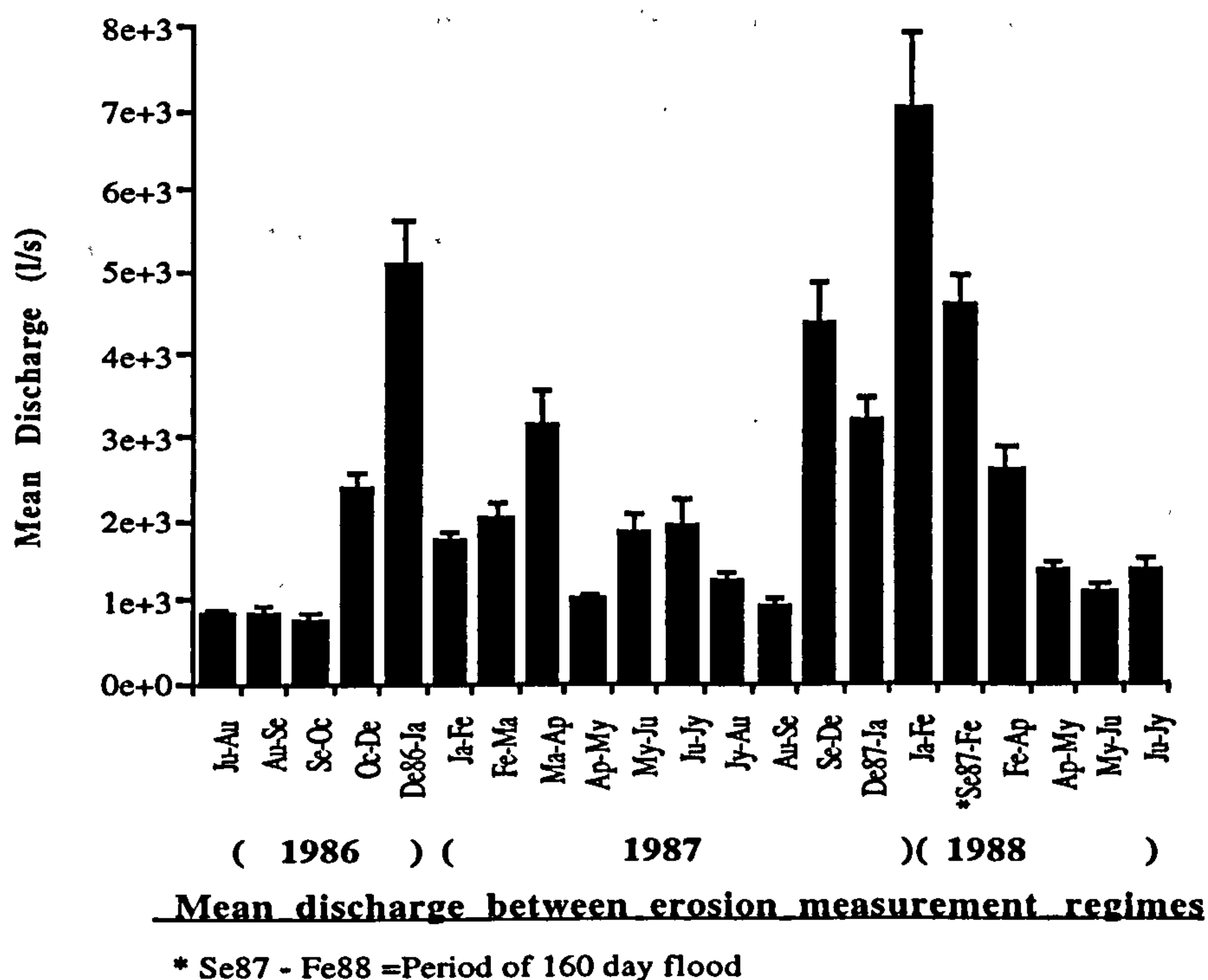


Fig. 3.5. : Comparison of Erosion within Bare Banks (Upper Bank Vs. Lower Bank)

Phase 2 (December 1986 to April 1987): The mid-bank region had been wetted by the first (October to December 1986) high flow. Winter cryergic activity (see 1.3; Lawler, 1986)) may have prepared the mid-bank region for the next stage which was the largest rate of erosion observed throughout this study.

Phase 3 (April to September 1987): May to September 1986 shows a reversal of the magnitudes of erosion from those of Phases 1 and 2. While the upper bank showed more erosion up to April 1987, the lower bank indicates a higher erosion of bare banks during the first summer following denudation. The explanation is that the recurrent high flows of the winter of 1986/87 were associated with a process of washing away of collapsed bank soil followed by erosion of the bank toe. This is in keeping with the pseudo-cyclic process of bank erosion observed by Knighton, for actively eroding banks.

Phase 4 (October 1987 to April 1988): The long storm flow levels of October 1987 to February 1988 shows not only a high rate of erosion of the mid bank but also the considerable amount of erosion recorded. This is ascribed not only to the intensity of flow but also possible creation of localised secondary isovels and vortices created by the isolation of these 5m long plots between well vegetated non-eroding adjacent banks.

Phase 5 (April to August 1988): Following the major floods of October 1987 to February 1988 there is a higher mean erosion on the lower bank than on the higher bank. This is similar to the observations made in Phase 3 above.

Conclusions :

i) on this reach of the river under ambient flow regimes, loss of vegetation leads to the following process:

(a) initial period of accelerated upper bank erosion; slumping associated with top soil destability caused by root death is suggested as the main reason for the initial high erosion;

(b) mid period of reduction of erosion to minimal levels within a few months;

(c) a third stage of a higher erosive effect on the upper banks than the lower banks;

this is associated mostly with storm flows;

iii) once the top soil has been eroded by the first storm flows and subsequent winter flows, summer erosion is more at the toe-region than the upper banks. This means that the lower layers of the bank profile (exposed as a result of the erosion of the top-soil), is more stable.

In essence, de-vegetation of banks by a systemic herbicide leads to an initial process of loosening up of the bank. The erosion of this top soil may either be dependent on the fluvial forces or independent (i.e due to gravitational forces).

3.4.2e Comparison of erosion within Naturally Vegetated banks (Upper versus Lower bank)

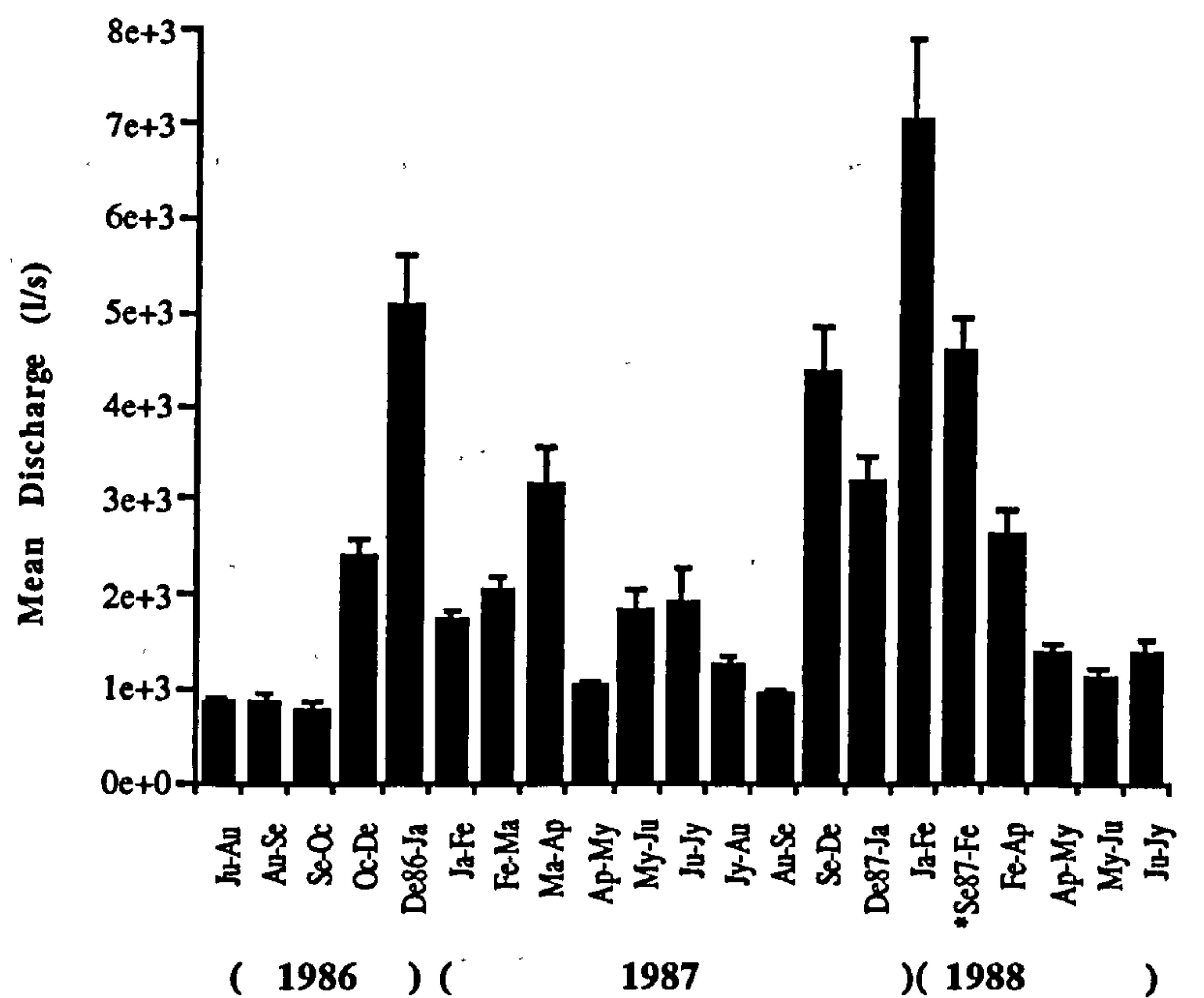
The main objects of this comparison were to find out the effects of naturally established vegetation on the following aspects, during different flow regimes:

- i) overall bank erosion (see Fig.3.2);
- ii) under-cutting in the lower bank at ambient flow regimes as discussed in 1.3.

As shown in Figures 3.2 and 3.6, overall erosion rates under natural vegetation are low. Mean erosion varied between 0.00mm/d (June to August 1986/summer) to 0.257mm/d during the latter part the winter storm flows of 1987/88.

Actively eroding banks observed by other authors such as Smith (1976), Hooke (1977a), and Simons et al (1979). Wolman and Leopold (1957) showed that for various sizes of rivers around the world, the lateral migration varied between 0 and 750 m/yr. The highest was that of the River Kosi in India.

Graphically (on a scale of 0 to 1.0 mm of erosion per day), there is very significant erosion in the lower region when compared with the upper region. But, in terms of the rates of erosion observed throughout the study for bare banks, the rates of erosion are much lower (less than 0.5mm /day even at its most vulnerable period of high flows after denudation) for the vegetated banks as discussed in 3.4.2a. At ambient flow such as June to October 1986 there has been almost no erosion in either of the defined regions (upper or lower) of the banks.



Mean discharge between erosion measurement regimes

* Se87 - Fe88 =Period of 160 day flood

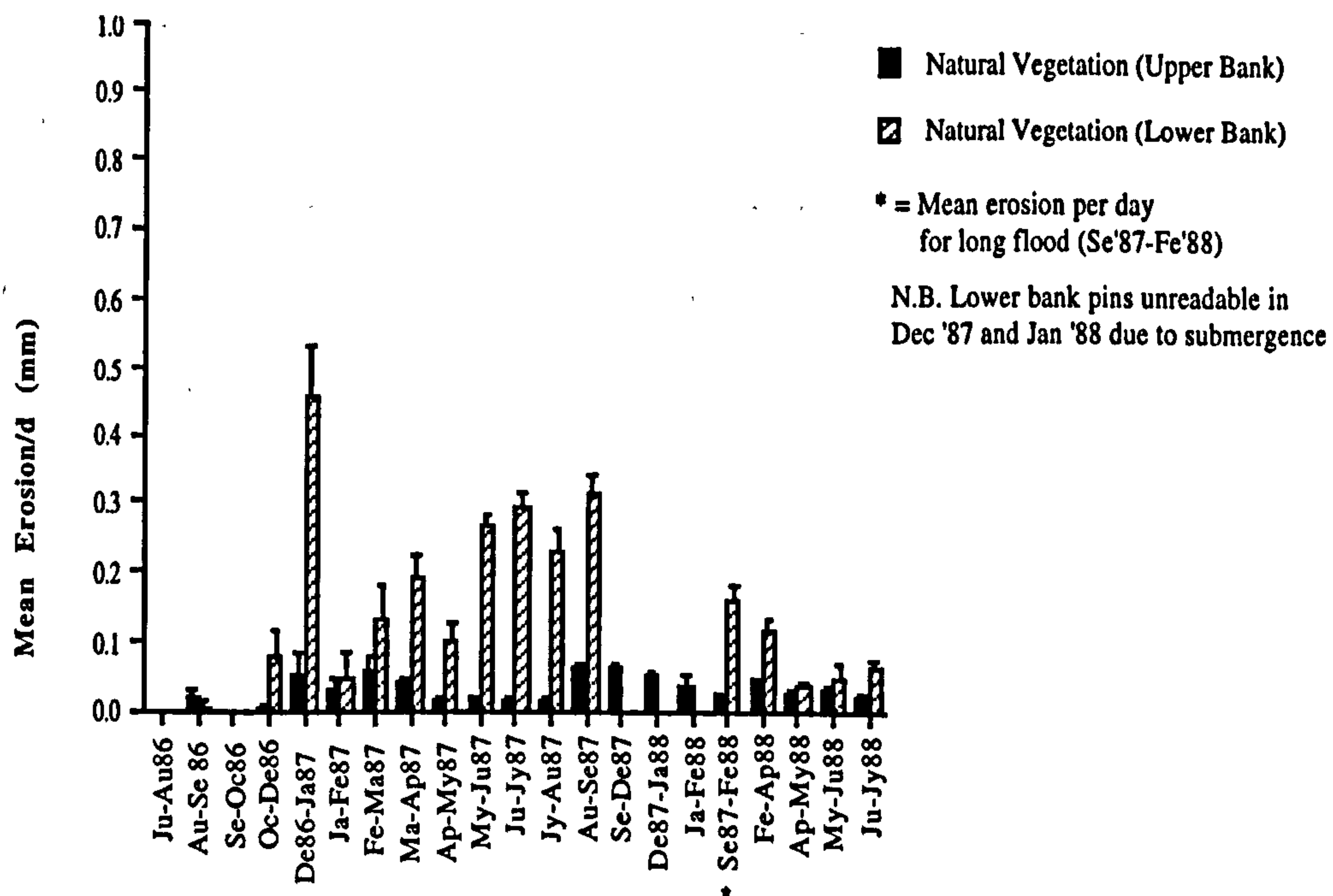


Fig.3.6 : Comparison of Erosion within Naturally Vegetated Banks (Upper Bank Vs. Lower Bank)

From December 1986 to September 1987 there is considerable erosion in the lower banks (minimum 0.05 to a maximum 0.15mm/d) while there is minimal erosion in the upper banks (range of 0.014 to 0.062mm/d). The important aspect to correlate with this is the higher mean discharge experienced during this period by the lower banks in particular and the whole bank in certain periods such as December 1986 to January 1987 and March to April 1987.

Closer examination indicates that during/after periods of flow with a maximum flow of above 2500 l-s approximately, the lower bank erosion commences (see. Fig.3.1 and 3.6). The significantly high erosion of the toe-region in December 1986 to January 1987 is attributed to the following observations:

- i) no vegetation cover in this region at this time of the year;
- ii) winter cryergic activity of the exposed wet, clay bank-toe soil to high erosion in the first high flow of winter;

Continuous undercutting is evident during the normally accepted 'non-erosive' summer periods. On closer examination with the maximum flows (Fig.3.1a) and mean discharges (Fig.3.1b) it is noted that the summer of 1987 was punctuated by periods of high flows and an 'above normal' mean discharge regime. Both these factors may have contributed to the higher undercutting/lower bank erosion.

These results indicate that the bank has a potential for long-term instability such as pseudo-cyclic slumping (Knighton,1984) discussed in 1.3. above. It was observed by the author during the study. But, the process of erosion >slumping >wash away of debris > erosion was of a small magnitude localised to the lower bank (upto 1m from the bank toe) when compared with the erosive processes in Phases 1 and 2 of the other experiments (see Chs. 4 & 5).

Conclusion

1. The main conclusion is that absence of the physical presence of toe-region vegetation results in continuous erosion of the bank toe-region.

3.4.2f A comparison of mean erosion for two consecutive winters between (i) a newly de-vegetated bank, and (ii) a long-standing naturally vegetated bank

Of the previous authors who attempted quantification of bank erosion under vegetation, Smith (1976) presents direct comparison of measured values. He used the erosion box technique (mass of soil eroded per unit time) and the erosion pin (lateral erosion in mm. per unit time) techniques. He estimated that vegetation offered 20,000 times more resistance to erosion for vegetated areas of the same river channel than for denuded areas. The measurements were carried out on a well vegetated bank with a 16 to 18 percent by volume of roots with a 5-cm root-mat for bank protection. Smith presumes that roots are the effective negators of bank erosion. He refrains from identifying a lower bank and an upper bank.

In this study the effects of vegetation are not presumed to be totally due to root effects. Therefore the following comparison, while seeking similar clarity and simplicity to that of Smith (1976) identifies two spatially contrasting regions on the river bank based on:

1. *Moisture regimes on the banks*

The lower bank (upto 0.75m from the bank-toe) is continuously under high/saturation moisture levels. The upper bank (above 0.75m from the bank-toe) is normally dry but periodically (mostly winter) saturated subject to changing flow levels in the river).

2. *Vegetational regimes*

The upper bank is well vegetated in summer and covered with skeletal foliage in winter. The lower bank is devoid of vegetation in summer and in winter.

NB. Summer erosion is not compared because

- (a) much of the summer erosion is minimal in the vegetated banks;
- (b) bare bank erosion in summer is not usually attributed to significant changes in channel flow because summer floods are rare;
- (c) to focus the scope of this thesis to traditionally accepted erosive periods.

Table 2 Comparison of mean erosion rates for two consecutive winters

	Sep-Oct	Oct-Dec	Dec-Jan	Jan-Feb	Mean Erosion for winter (Sep- Feb)period (mm-d)
Bare					
Upper bank (1986/87)	0.46 ± 0.11	0.33 ± 0.06	2.89 ± 0.44	0.62 ± 0.11	1.07
Lower bank (1986/87)	0	0.06 ± 0.02	0.87 ± 0.34	0.29 ± 0.10	0.30
Upper bank (1987/88)	*	(Sep-Dec) 1.30 ± 0.06	1.25 ± 0.05	0.43 ± 0.02	0.99
Lower bank (1987/88)	*	*	*	(Sep-Feb) 0.48 ± 0.04	0.48
Natural Vegetation					
Upper bank (1986/87)	0	0.01 ± 0.00	0.06 ± 0.03	0.03 ± 0.01	0.025
Lower bank (1986/87)	0	0.08 ± 0.04	0.45 ± 0.08	0.05 ± 0.03	0.145
Upper bank (1987/88)	*	(Sep-Dec) 0.06 ± 0.01	0.05 ± 0.05	0.04 ± 0.02	0.05
Lower bank (1987/88)	*	*	*	(Sep-Feb) 0.16 ± 0.02	0.16

* Due to the persistent floods pin readings could not be measured during these periods.

** Each cell represents the mean erosion recorded for the treatment. Each treatment contained six plots; Each plot had six pins on the upper bank and 3 pins on the lower bank (for Sep.1986 - March.1987) or twenty one pins on the upper bank and seven pins on the lower bank (from April 1987 onwards); (see Figs. 2.8a and 2.8b for description of pin positions);

Table 2 above compares the rates of mean erosion (mm^{-d}) of a naturally vegetated bank with that of a Bare bank during two contrasting fluvial regimes of two consecutive winters. In 3.4.2a, p.104, an introduction on the conditions prevalent during the two winters was presented.

The mean erosion in each cell for periods (eg. Sep-Oct as shown above) is calculated from a total number of pin readings for each treatment as:

Upper bank: 6x6=36 (Sep. 1986 - March 1987) and 21x6=126 (April 1987 - onwards);

Lower Bank: 3x6=18 (Sep. 1986 - March 1987) and 7x6=42 (April 1987 - onwards);

On the Bare banks, following the top-soil de-stabilisation caused by application of the systemic herbicide, the winter of 1986/87 is the first winter of high flows. It is expected to be a period of high erosion. Following the wash away of the de-stabilised top soil, the expectation is that the more stable lower layers of the bank soil will be exposed to the second winter (1987/88) erosion.

On the above basis of clearly defined intra-bank differences and inter-bank differences (Normal vegetation versus Bare banks), a multiplicity of permutations of comparisons are possible. The main reason for comparisons of the two winter periods is that winter is associated with high flow levels. This fact is amply demonstrated in Figs. 3.1a and 3.1b. As such the erosion for the two treatments are attributed to fluvial forces within the channel. All erosion data in the periods shown in Table 2 (eg. Sep-Oct) are mean erosion rates (mm/day). The mean erosion rates were calculated from the database of the individual erosion pin data for the main experiment (see App. 4a and 4b for summary of calculated mean erosion data for all experiments/treatments).

Conclusions

- i) On average the bare banks are over seven times more erosive than the normal vegetation. ($1.07+0.30+0.99+0.48=2.84\text{mm}$ for Bare; $0.025+0.145+0.05+0.16=0.38\text{mm}$) for natural vegetation; a ratio of 7.47:1.**
- ii) for the bare banks, the upper bank areas were approximately four times more erodible than the lower bank for the first winter ($1.07/0.30 = 3.56$); for the second winter of longer high flows it was more than twice ($0.99/0.48=2.06$). This indicates the extent of instability brought about by denudation of naturally established bank vegetation by the application of a systemic herbicide prior to a 'normal winter flow'.**
- iii) for the naturally vegetated banks the recorded average sediment yield per position on lower banks was approximately six times that of the upper bank recorded for the first winter of observation ($0.145/0.025 = 5.8$); Obviously there is a highly significant process of undercutting prevalent during winter flow in the basal region of the banks of this river.**

In the long, steady high flows of the subsequent winter, the toe-region of the vegetated banks showed three times the erosion ($0.16/0.05 = 3.2$) of the upper banks. This may be proposed as a significant potential erosion of the toe-region in the absence of semi-aquatic toe-protective plants. As there is no comparison available for erosion under such fringe vegetation this is a simplistic mode of approach for predictive purposes. However, it is a valid argument on the potential erodibility of a bank where the upper bank colonisers eliminate the potential lower bank colonisers by competitive exclusion (eg. by shading) thereby leading to bare lower banks. In such a situation the theory of 'natural stabilization' (see Table 1.1 and Section 1.1.1) of newly constructed or actively eroding channel banks is questionable. Such measures of 'non-management' may compound the process of initiation of erosion by exposing potentially vulnerable (in terms of erodibility by fluvial forces) positions of bank-toe soil. The process of undercutting at these positions will be more severe during bankful flow as the fluvial forces are much higher at the toe-region than at the upper banks during such flows (Knighton, 1984). Once such undercutting commences the 'pseudo-cyclic' (Knighton, 1984) process of lower bank failure followed by upper bank failure may continue. Such indirect encouragement of lower bank erosion by certain upper bank species as a result of inter-specific competition emphasises the nature of ambiguity in recommending a totally unmanaged process of natural revegetation.

3.4.2g. Main Conclusions

A comparison of the different relative magnitudes of erosion at the toe region and the bank above, for both vegetated and bare banks indicates a higher relative rate of erosion at the toe-region of the vegetated banks. It indicates continuous undercutting during summer in the toe region under naturally vegetated banks. The magnitude (mean erosion) of such undercutting varies between 0 to 0.4mm d^{-1} . The reasons for and implications of this form of undercutting are discussed in 3.4.2f above.

3.4.3 A study of Shear Strength and Moisture Content variations on (a) Bare banks and (b) Naturally vegetated banks

The reasons for choosing to quantify these parameters were stated in 2.1 and 2.2. Unlike dryland slopes, wetland slopes with active fluvial processes are subject to :

- i) an almost constant moisture profile for different heights up the bank at ambient flow;
- ii) a saturated long-term high moisture regime under long-term storm flows as prevalent in this study in the winter of 1987. The aims of the experiment as set out in 3.1.1. further clarify the necessity for understanding this tripartite relationship (see 3.4.4.) which may have a direct influence on the erosion of the banks both at ambient flow and storm flow regimes. The reasons for the choice of February, May and August as suitable months for the measurements were given in 2.5 above.

Aims v, vi, of 3.1.1. are addressed in the following analysis. In section 3.4.4, aim viii is addressed as root measurements were carried out only in February, May and August 1988. The discussion and conclusions on the relationships of the variations of shear strengths and moisture contents (subject of 3.4.3 herewith) will be condensed in an attempt to limit the size of the thesis. In addition much research literature is available from Nichols (1932) to Ohu et al (1986) and Ayres (1987) on the relationship between moisture content variations and shear strength on various types of soils . It is possible to discuss the variations of shear strengths and/or moisture content on a lengthy individual basis for each plot for August 86, February, August 87 and February, May, August 88. What is sought in this study is more the observation of a pattern of changes on the main aspects (shear strength and moisture content of the soil) with the conclusions based on possible causes and effects between the bare soil and the two species of natural vegetation (*E. hirsutum* and *U. dioica*) ;

The analysis is carried out on three representative plots (1a, 3a, and 5a; see Fig.2.3). They are :

- a) Bare banks represented by Plot 1a;
- b) Natural vegetation dominated by *Epilobium hirsutum* represented by Plot 3a;
- c) Natural vegetation dominated by *Urtica dioica* represented by Plot 5a;

Plot 3a had *Epilobium hirsutum* (see Plate 5) as the predominant mid-region vegetation with hardly any plants arising below level 1, (i.e. 50cm from the bank-toe) while Plot 5a was predominantly vegetated with *Urtica dioica* between levels 1 to 3 (see Plate 6). In addition, Plot 5a had more grasses, mainly *Poa spp.* sparsely vegetated between levels 2 to 4.

Figure 2.4 together with Sections 2.3.3 and 2.3.4 explain the measurement regimes for shear strength and moisture content values. The graphical presentation of data and the statistical analysis is based on the mean values per position of sampling as indicated in Fig. 2.4.

August '86	February'87	August '87	February'88	May '88	August.'88
Bare	Bare	Bare	Bare	Bare	Bare
Plot 1a	Plot 1a	Plot 1a	Plot 1a	Plot 1a	Plot 1a
Natural Vegetation dominated by <i>E. hirsutum</i>	Natural Vegetation dominated by <i>E. hirsutum</i>	Natural Vegetation dominated by <i>E. hirsutum</i>	Natural Vegetation dominated by <i>E. hirsutum</i>	Natural Vegetation dominated by <i>E. hirsutum</i>	Natural Vegetation dominated by <i>E. hirsutum</i>
Plot 3a	Plot 3a	Plot 3a	Plot 3a	Plot 3a	Plot 3a
Natural Vegetation dominated by <i>U. dioica</i>	Natural Vegetation dominated by <i>U. dioica</i>	Natural Vegetation dominated by <i>U. dioica</i>	Natural Vegetation dominated by <i>U. dioica</i>	Natural Vegetation dominated by <i>U. dioica</i>	Natural Vegetation dominated by <i>U. dioica</i>
Plot 5a	Plot 5a	Plot 5a	Plot 5a	Plot 5a	Plot 5a

Table 3.3 Time sequence of bank shear strength and moisture content study

N.B. August 1986, '87 and '88 are considered of most significance due to impending winter flows and high erodibility arising from fluvial forces.

3.4.3a August 1986

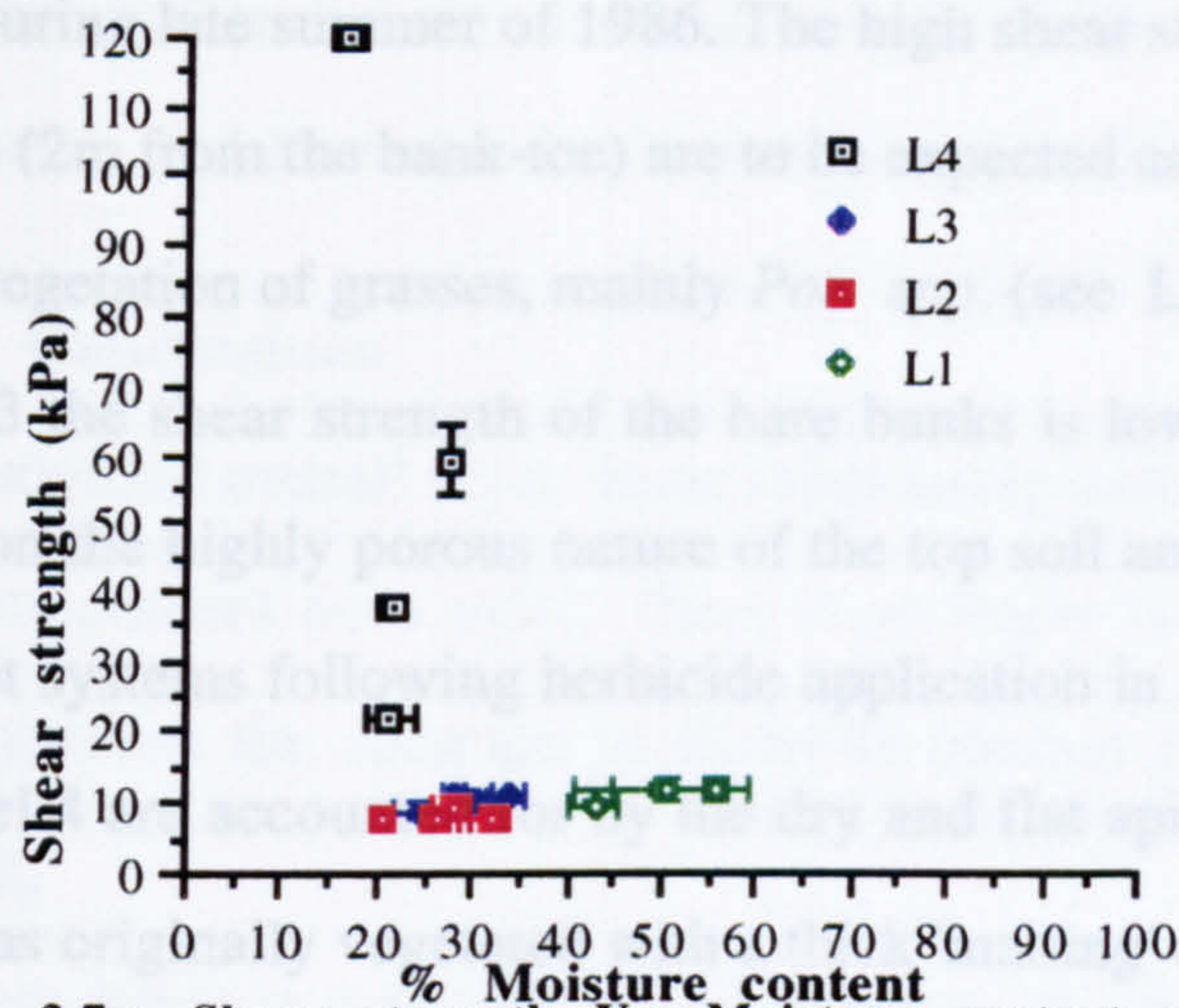


Fig. 3.7a: Shear strength Vs. Moisture content variations (August 1986) on Bare banks

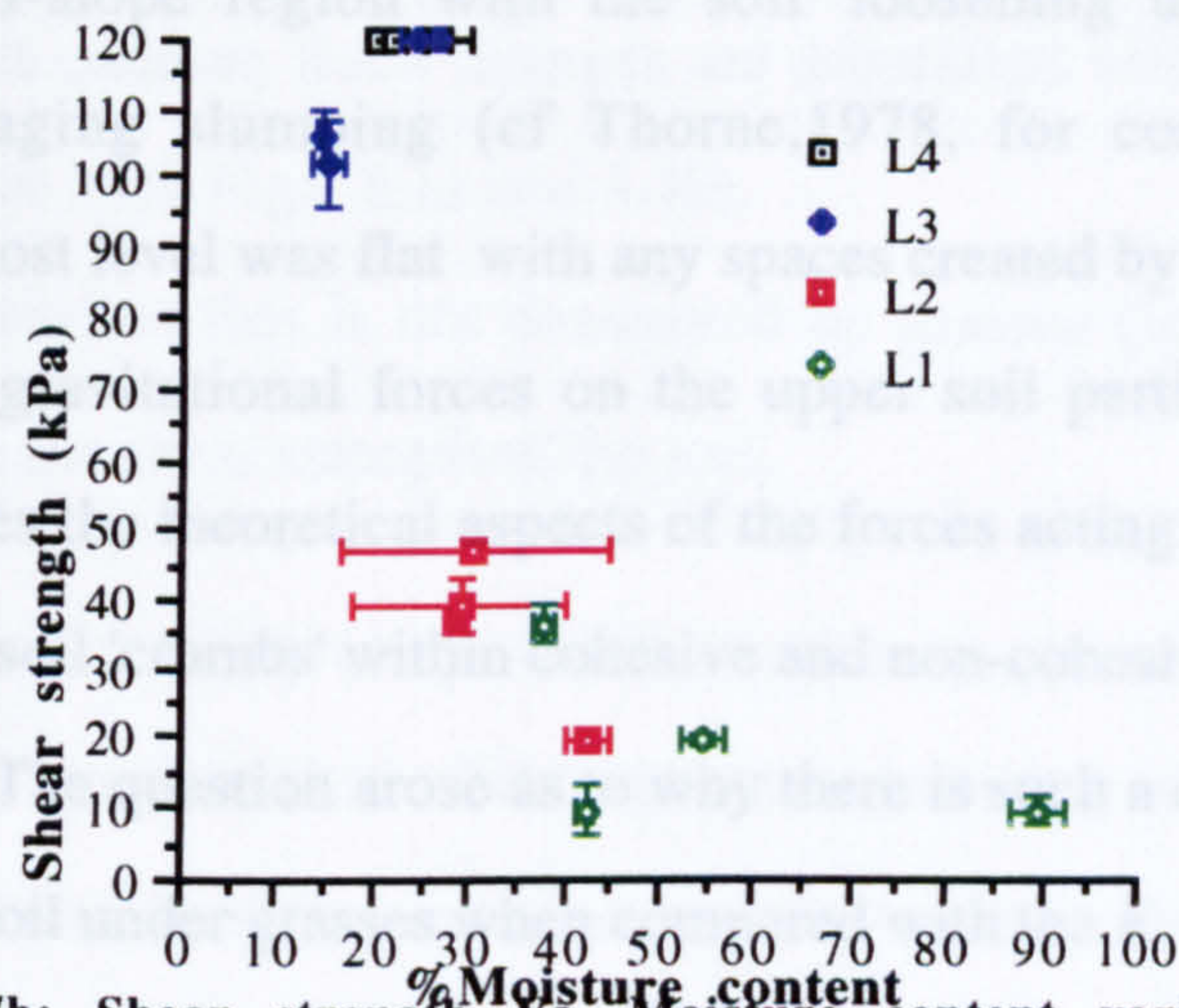


Fig. 3.7b: Shear strength Vs. Moisture content variations (August 1986) on Naturally vegetated banks dominated by *E. hirsutum* at levels 3 & 4

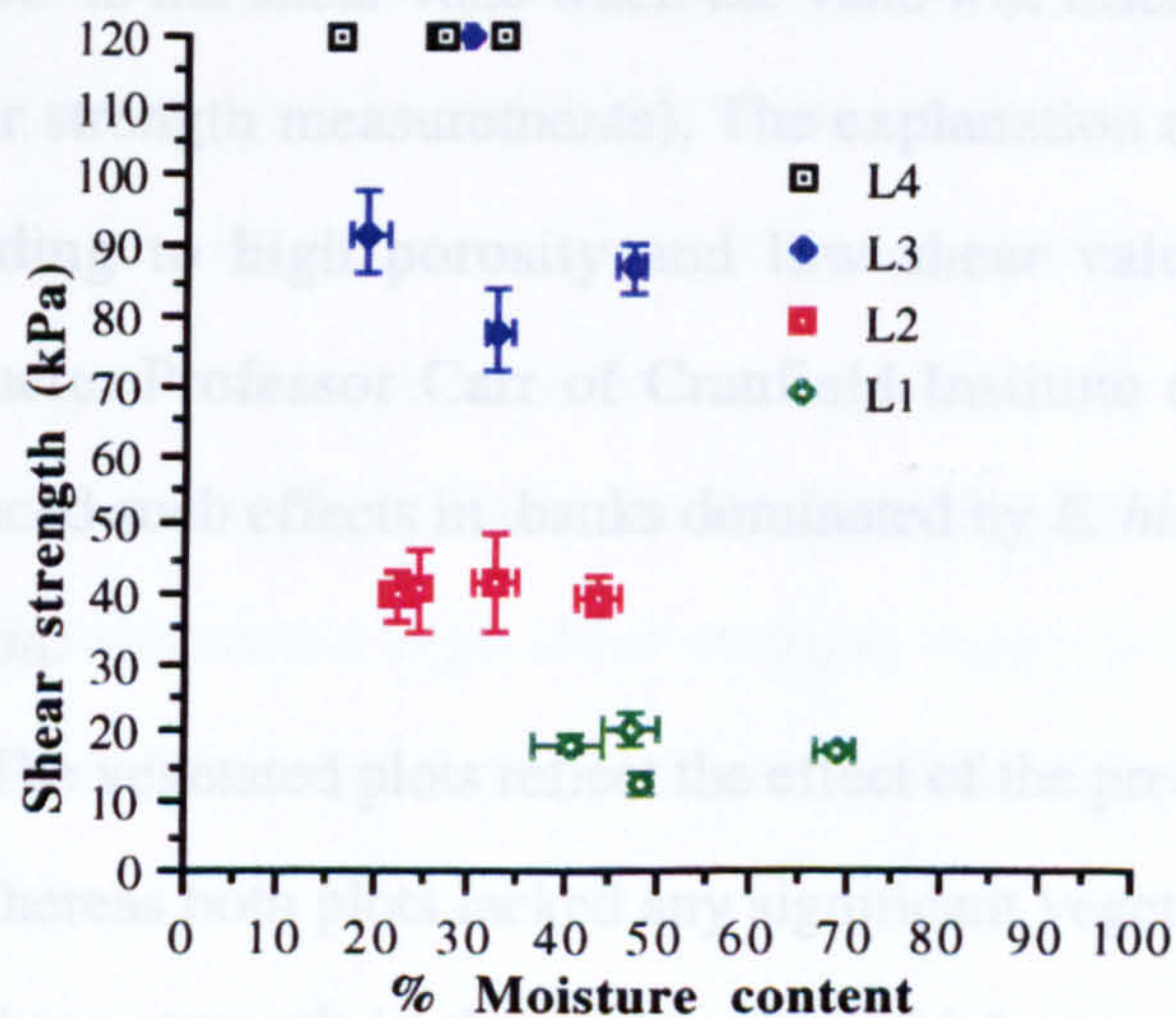


Fig. 3.7c: Shear strength Vs. Moisture content variations (August 1986) on Naturally vegetated banks dominated by *U. dioica* at levels 2 to 4

Figs. 3.7a, 3.7b, and 3.7c, depict the situation at ambient flow regime of the river during late summer of 1986. The high shear strength and low moisture contents at level 4 (2m from the bank-toe) are to be expected as this level was occupied mainly by a thick vegetation of grasses, mainly *Poa spp.* (see List of species in 2.2.1f). At Levels 1, 2 and 3 the shear strength of the bare banks is low. This is in keeping with the notes made on the highly porous nature of the top soil and the dead and decaying remains of the root systems following herbicide application in June 1986. The high shear strengths at Level 4 are accounted for by the dry and flat apical position of the bank slope. This area was originally vegetated with a thick 'matting' of grass at the time of application of the herbicide. Another explanation is that while the mid-bank at Levels 2 and 3 were in the mid-slope region with the soil 'loosening up' due to the death of the roots encouraging slumping (cf Thorne, 1978, for confirmation of phenomenon), the uppermost level was flat with any spaces created by the death of roots being compacted by the gravitational forces on the upper soil particles. Thorne (1978; pp 39 to 67) discusses the theoretical aspects of the forces acting on a particle at the bank surface as well as soil 'crumbs' within cohesive and non-cohesive bank soils.

The question arose as to why there is such a difference in the 'resistance' offered by the soil under grasses when compared with the *E. hirsutum* dominated banks. Plot 3a which had the mid-bank (levels 2 and 3) vegetated with *E. hirsutum* offered less resistance to the shear vane when the vane was inserted (prior to turning the vane head for shear strength measurements). The explanation may be the loosening effect on the soil leading to high porosity and low shear values associated with *E. hirsutum* rhizosphere. Professor Carr of Cranfield Institute of Technology (pers.comm.), had experienced such effects in banks dominated by *E. hirsutum* and certain other species of vegetation.

The vegetated plots reflect the effect of the presence of the vegetation types on the plots. Whereas both plots lacked any significant vegetation at Level 1, Plot 3a indicates a higher shear strength in the mid-region which was virtually a mature monoculture of *E. hirsutum* (see Plate 5). The vegetation in Plot 5a constituted mainly of *U. dioica* and a

sparse growth of grasses (at Levels 3 and 4) indicates a lowering of shear strength of the soil with similar moisture contents to that of Plot 3. This led to the idea of including *E.hirsutum* and *U. dioica* in a separate intensive survey (see Ch.6).

Main Conclusions

- i) the expected overall curvi-linear relationship between shear strength of the soil and its moisture content does exist; there is no linear correlation (see Figs. 3.7.a, 3.7b and 3.7c) between the decrease in moisture content of the soil and increase in its shear strength;
- ii) the gradation in reduction of soil moisture content upwards from the base of the bank is clearly evident, but the mid region is more susceptible to changes in the percentage moisture content; Such changes are associated with previous or current flow regimes (compare with Figs. 3.1a and 3.1b).
- iv) vegetation that is not dominated by grasses (levels 2 and 3) does not necessarily increase the shear strength of the soil;

3.4.3b February 1987

Figs. 3.8a, 3.8b, 3.8c, indicate a lowering of shear strength values in the upper banks (level 4) of the measured plots, as compared with the previous summer readings. This is attributed to the differences in the dry conditions prevailing in August to September 1986 and the changes imparted to the soil by the subsequent floods of winter 1986/87 (see Figs. 3.1a and 3.1b). Research literature is limited to studies of changes in shear strength and moisture content of a given soil within short periods of time and not that of long term saturation. Another explanation is that the winter floods and the death of roots in winter contributed to this lowering of shear strength. Yet the upper bank (Level 4) maintains a high shear strength value in the vegetated plots. This may be a direct result of the vegetation type (dense growth of grasses) that was prevalent at level 4 of the bank.

The most striking feature in February is the marked decline in shear strength of the upper bank in bare plots and the generally drier nature of this upper bank in comparison with the vegetated banks. The explanation lies in two aspects :

- i) the exposed bare bank has a higher evaporation from the top-soil ;
- ii) the vegetated plots are covered with a protective layer mainly in the form of the leaf litter from the previous autumn.

Conclusions

- i) winter period is associated with a higher moisture content of the banks; this is applicable to both bare and naturally vegetated banks;
- ii) vegetated banks have a higher moisture retention capacity in winter as shown in 3.8b and 3.8c. This is due mainly to less evaporation through the available sparse foliage in winter and to the presence of dead leaves covering the soil thereby preventing direct evaporation from the soil;
- iii) Level 3 in both types of natural vegetation indicate a higher shear strength (by 20 - 40 kPa) in February 1987 (winter) than in the previous autumn. It contradicts the hypothesis that actively growing plants would contribute to increase in shear strength of the soil as opposed to 'wintering' plants.
- iv) Bare banks show similar curvilinear relationships of shear strength and moisture content to naturally vegetated banks. While the author expected a clearer positive relationship in terms of increase in shear strengths related to natural vegetation, there is no marked evidence from this experiment.

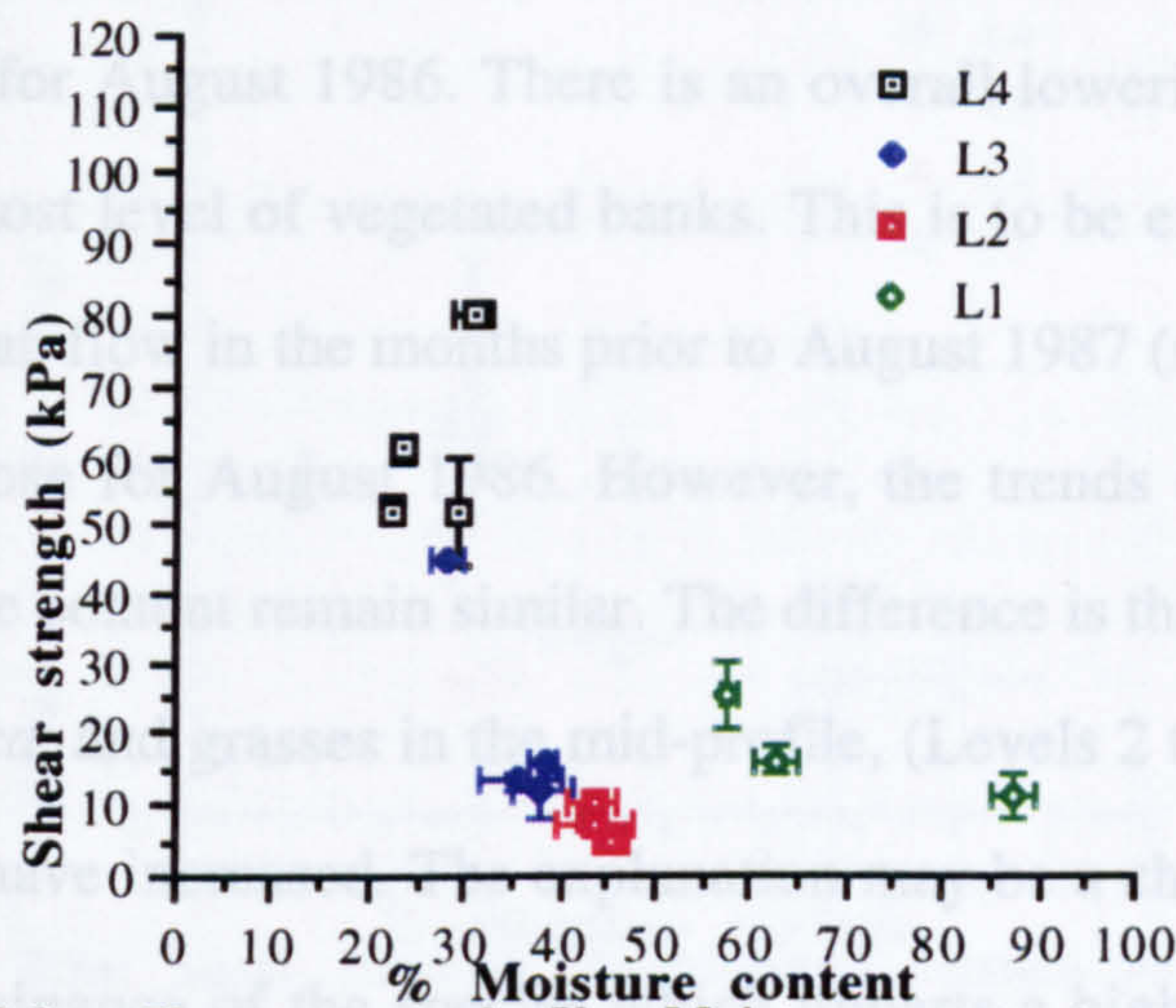


Fig. 3.8a: Shear strength Vs. Moisture content variations (February 1987)
on Bare banks

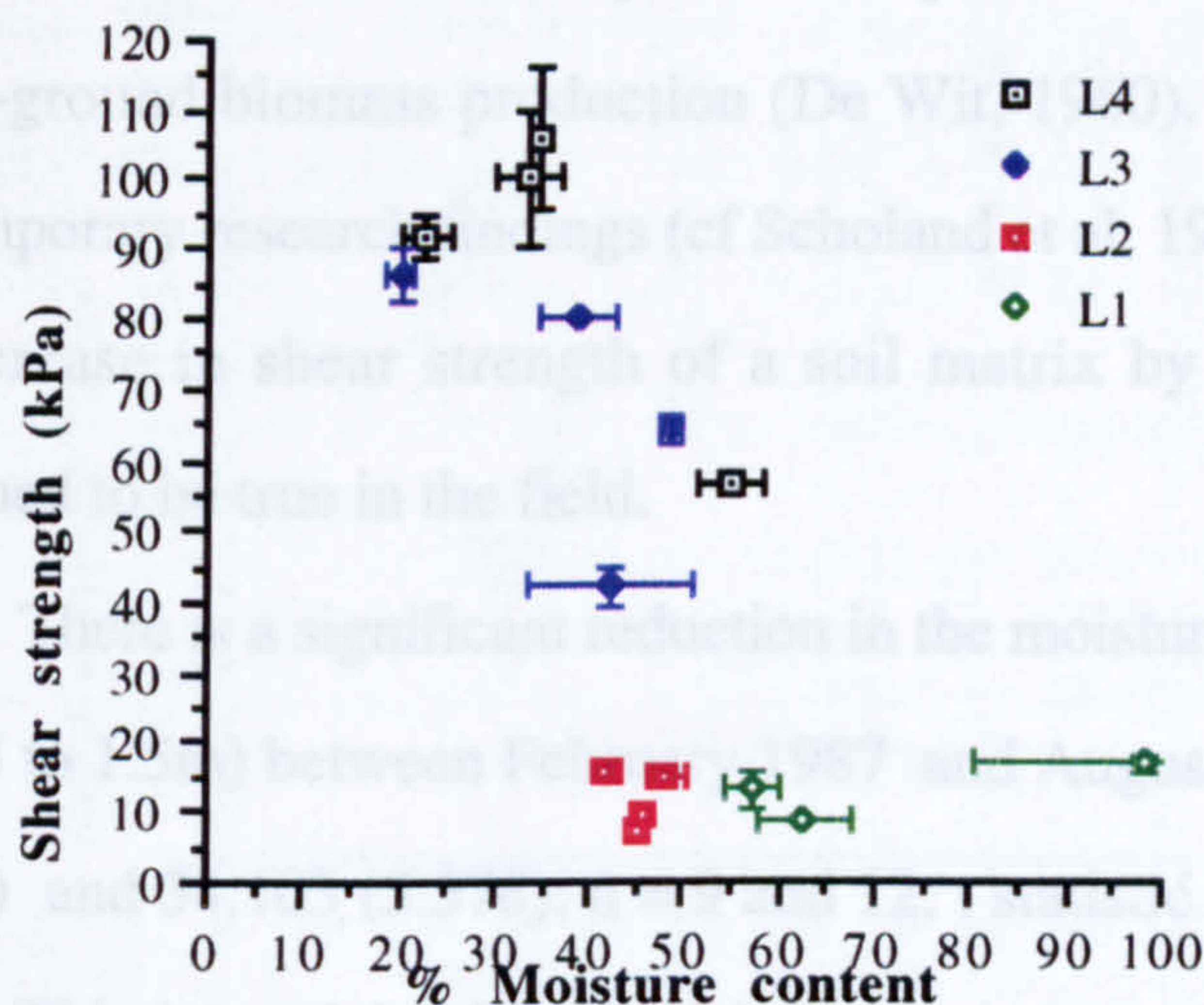


Fig. 3.8b: Shear strength Vs. Moisture content variations (February 1987)
Naturally vegetated banks dominated by *E. hirsutum* at levels 2 to 4

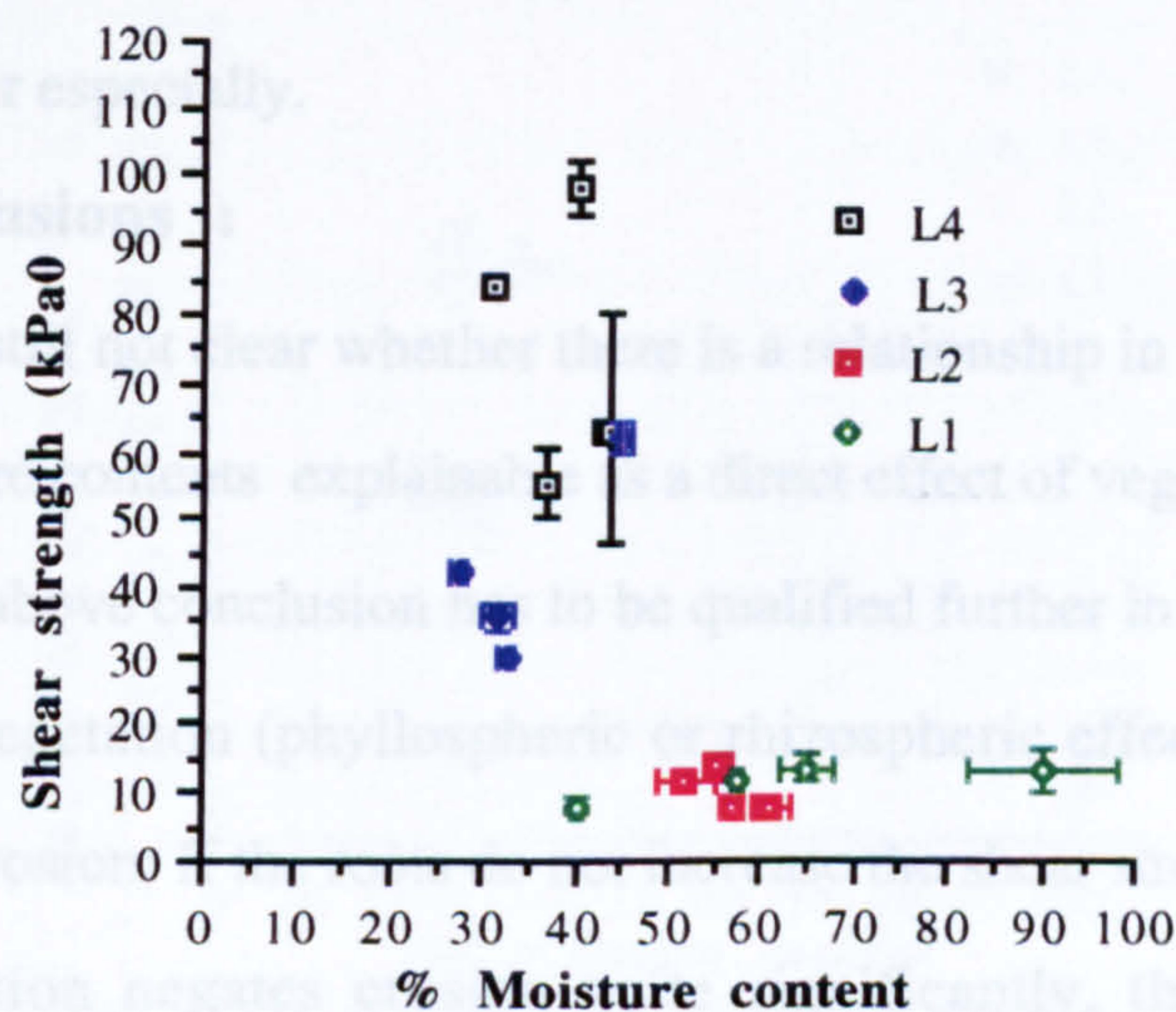


Fig. 3.8c: Shear strength Vs. Moisture content variations (February 1987)
Naturally vegetated banks dominated by *U. dioica*

3.4.3c August 1987 Figs. 3.9a, 3.9b, 3.9c could be compared with the results for August 1986. There is an overall lowering of shear strength values for the uppermost level of vegetated banks. This is to be expected as both the maximum flow and mean flow in the months prior to August 1987 (see Figs. 3.1a and 3.1b) were higher than those for August 1986. However, the trends of variation of shear strength with moisture content remain similar. The difference is that in Plot 5 (Natural vegetation with *U. dioica* and grasses in the mid-profile, (Levels 2 to 3 in Fig. 3.9c) the shear strength values have increased. The explanation may be a change in density of either species or the dominance of the species which imparts a higher shear strength to the soil. Such phenomena as intra- or inter-specific competitive effects bear a significant importance in below-ground biomass production (De Wit, 1960). However, in the current context of contemporary research findings (cf Scholander et al, 1991) previously accepted phenomena (of increase in shear strength of a soil matrix by increased root density) cannot be presumed to be true in the field.

There is a significant reduction in the moisture contents on the bare banks at level 3 (0.75 to 1.5m) between February 1987 and August 1987. The mean values are 44.017 (0.862) and 34.103 (5.578); $n = 9$ and 12 ; t statistic = 3.653 and significance = 0.015.

This is explained by the higher moisture content on the bare banks during the winter period and greater exposure to evaporation during dry weather of late spring and summer especially.

Conclusions :

- i) it is still not clear whether there is a relationship in the variations of shear strength and moisture contents explainable as a direct effect of vegetation on the banks;
- ii) the above conclusion has to be qualified further in terms of which component/s of the bank vegetation (phyllospheric or rhizospheric effects) are important in prevention of bank erosion; If the roots do not increase the shear strength of the soil but the presence of vegetation negates erosion quite significantly, then one has to discount the first hypothesis (i.e. roots of bank vegetation increase the shear strength of the soil beyond its

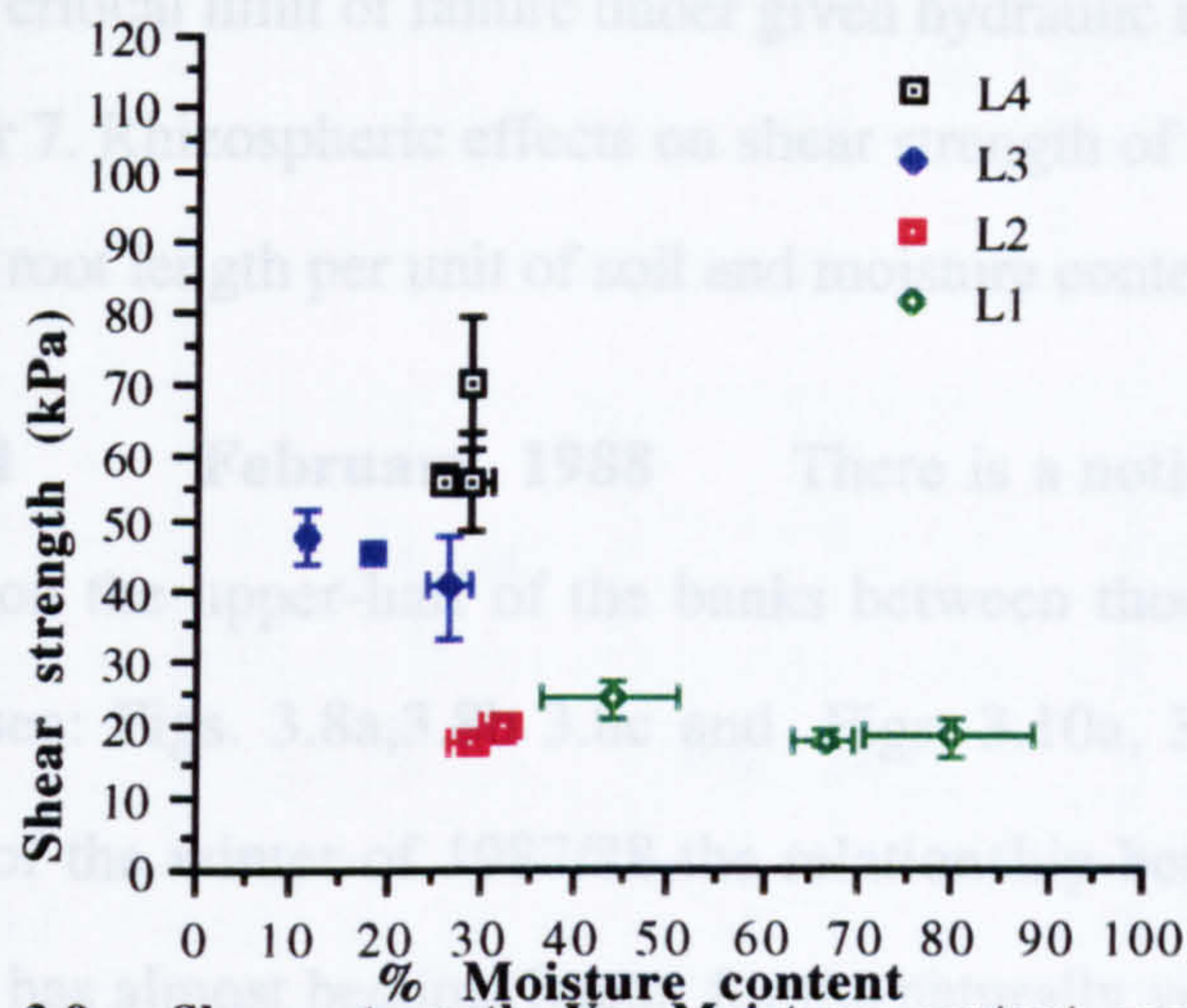


Fig. 3.9a: Shear strength Vs. Moisture content variations (August 1987)
Bare Banks

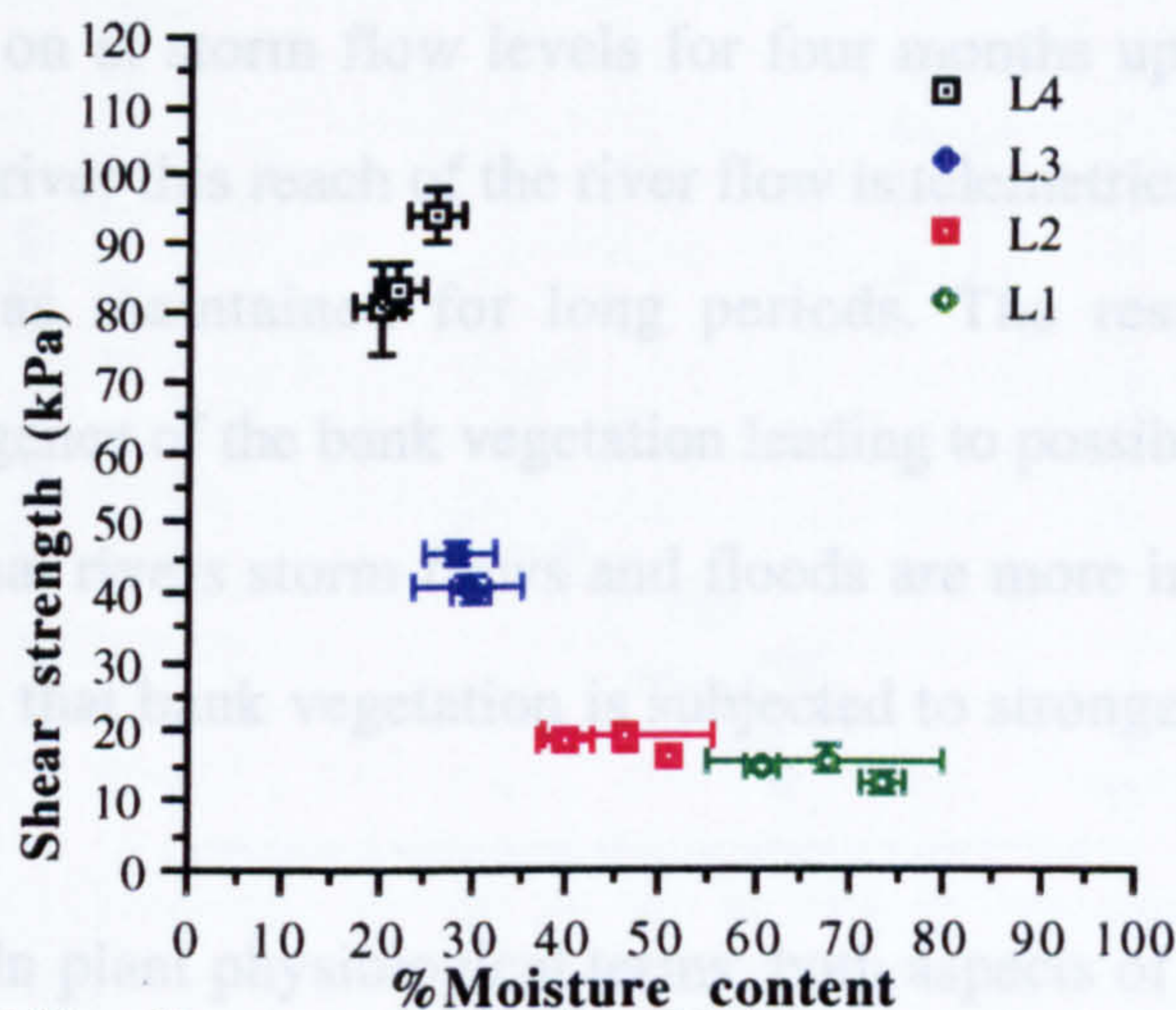


Fig. 3.9b: Shear strength Vs. Moisture content variations (August 1987)
Naturally vegetated banks dominated by *E. hirsutum*

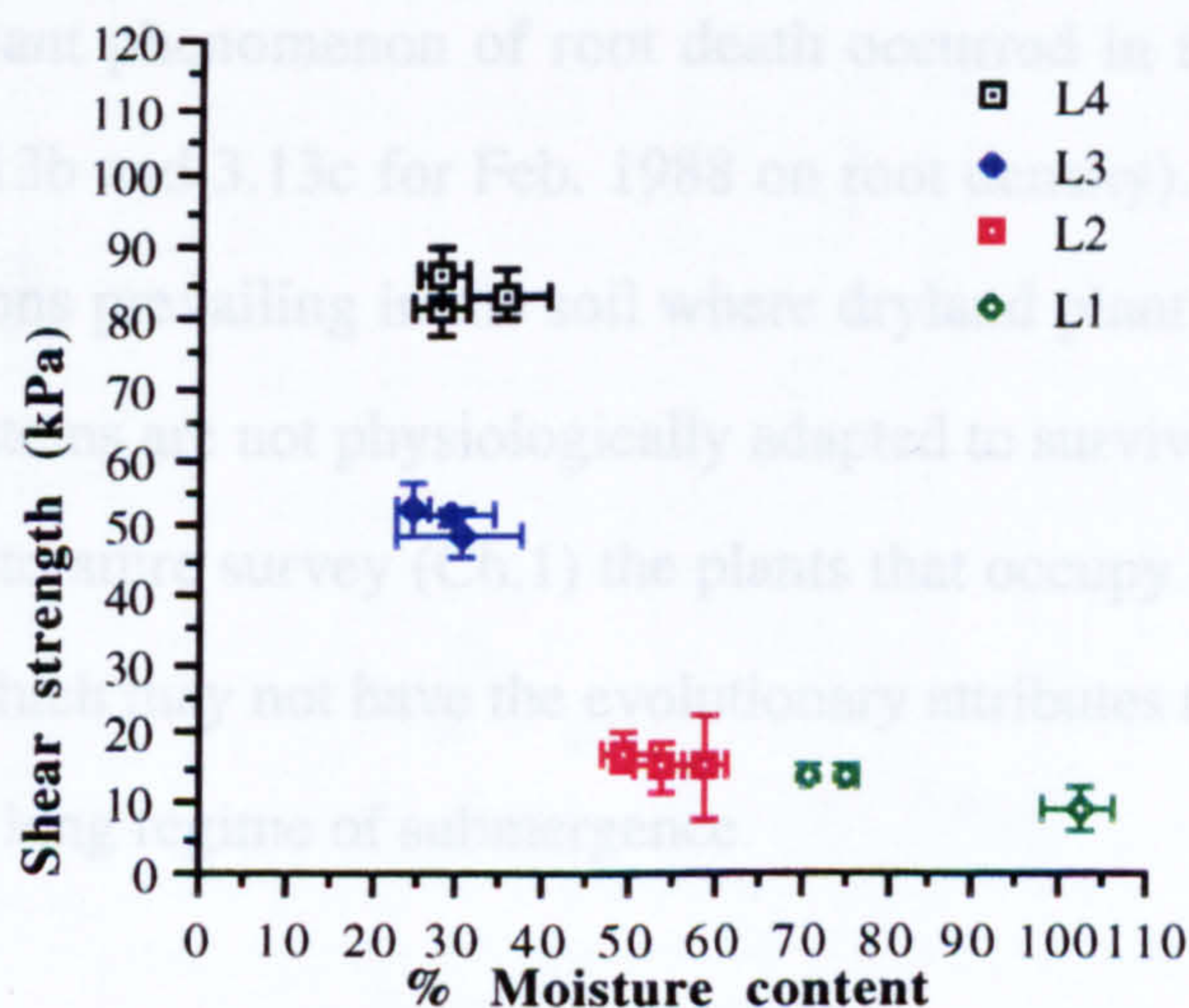


Fig. 3.9c: Shear strength Vs. Moisture content variations (August 1987)
Naturally vegetated banks dominated by *U. dioica*

normal critical limit of failure under given hydraulic regimes). This is further discussed in Chapter 7. Rhizospheric effects on shear strength of the bank soil are discussed in terms of total root length per unit of soil and moisture content variations in 3.5.4.

3.4.3d February 1988 There is a noticeable difference of shear strength values on the upper-half of the banks between those of February 1987 and February 1988 (see: Figs. 3.8a,3.8b 3.8c and Figs. 3.10a, 3.10b, 3.10c). After the prolonged floods of the winter of 1987/88 the relationship between shear strength and moisture content has almost become linear for the naturally vegetated banks. The explanation of this significant change may be in the long flood that commenced in October 1977 and carried on at storm flow levels for four months upto January 1988. As opposed to a normal river this reach of the river flow is telemetrically controlled. Continuous bankful flow was maintained for long periods. The result was that of long continuous submergence of the bank vegetation leading to possible root death and accelerated decay. In normal rivers storm flows and floods are more intense but of shorter duration. The result is that bank vegetation is subjected to stronger lateral fluvial forces that subside quickly.

In plant physiological terms, both aspects of long-term submergence stress and anaerobic conditions under submergence contribute to death and decay. It may be that a significant phenomenon of root death occurred in the naturally vegetated banks (see Figs.3.13b and 3.13c for Feb. 1988 on root density). This may be due to the anaerobic conditions prevailing in the soil where dryland plant (upper bank is occupied by these) root systems are not physiologically adapted to survive long submergence. As concluded in the literature survey (Ch.1) the plants that occupy the bank profile above Level 1 are those which may not have the evolutionary attributes to survive the conditions prevailing under a long regime of submergence.

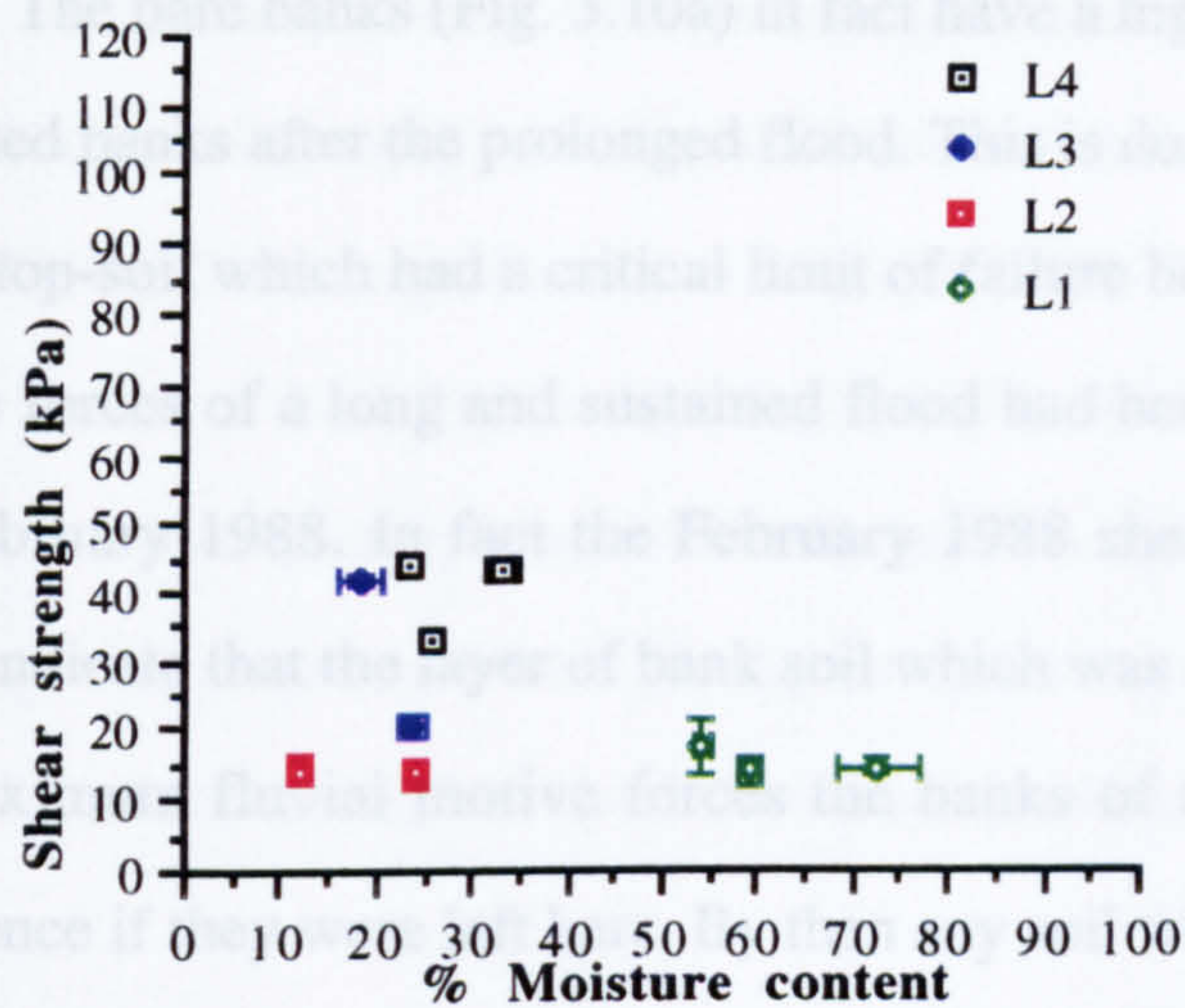


Fig. 3.10a: Shear strength Vs. Moisture content variations (February 1988)
Bare Banks

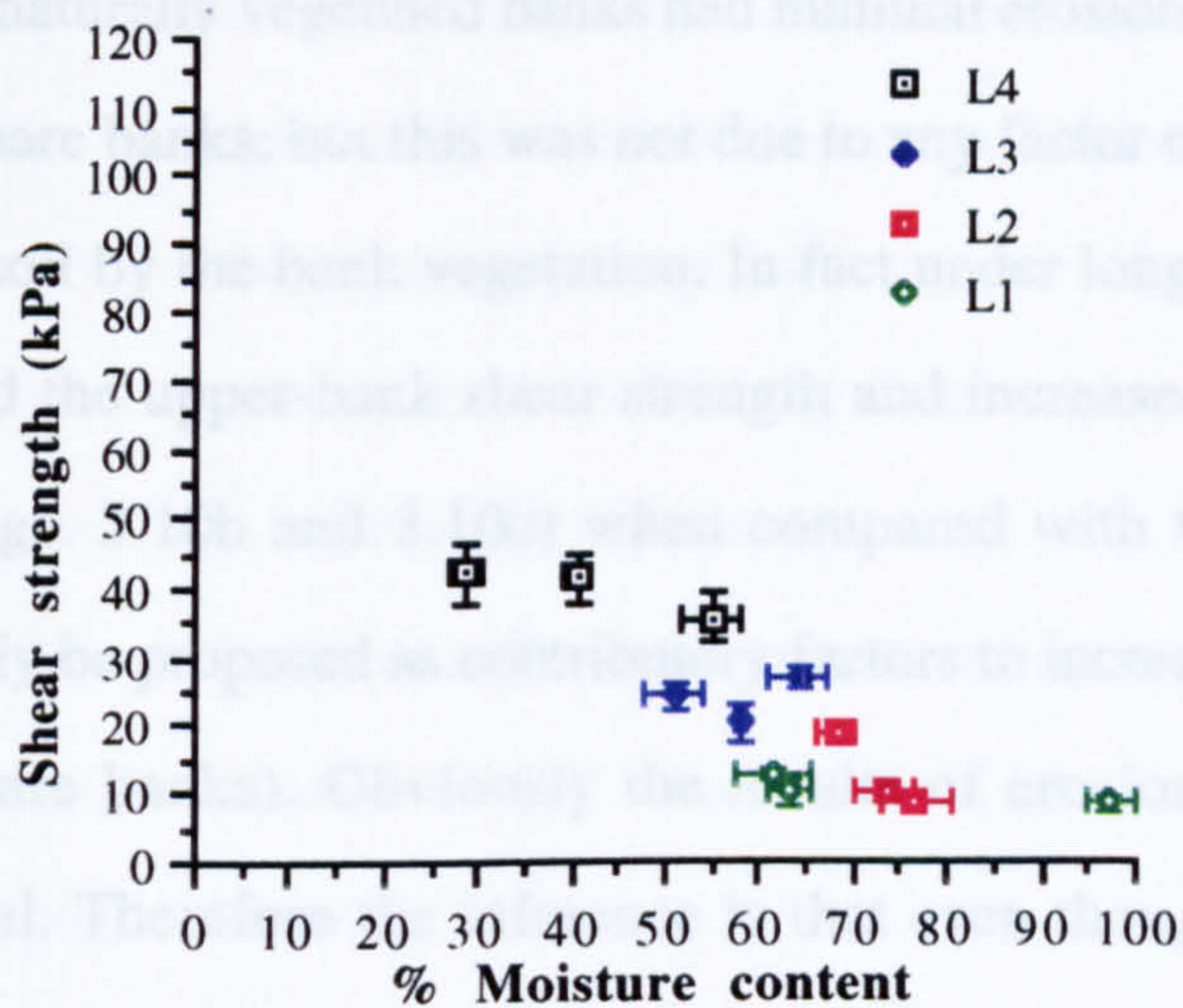


Fig. 3.10b: Shear strength Vs. Moisture content variations (February 1988)
Naturally vegetated banks dominated by *E. hirsutum*

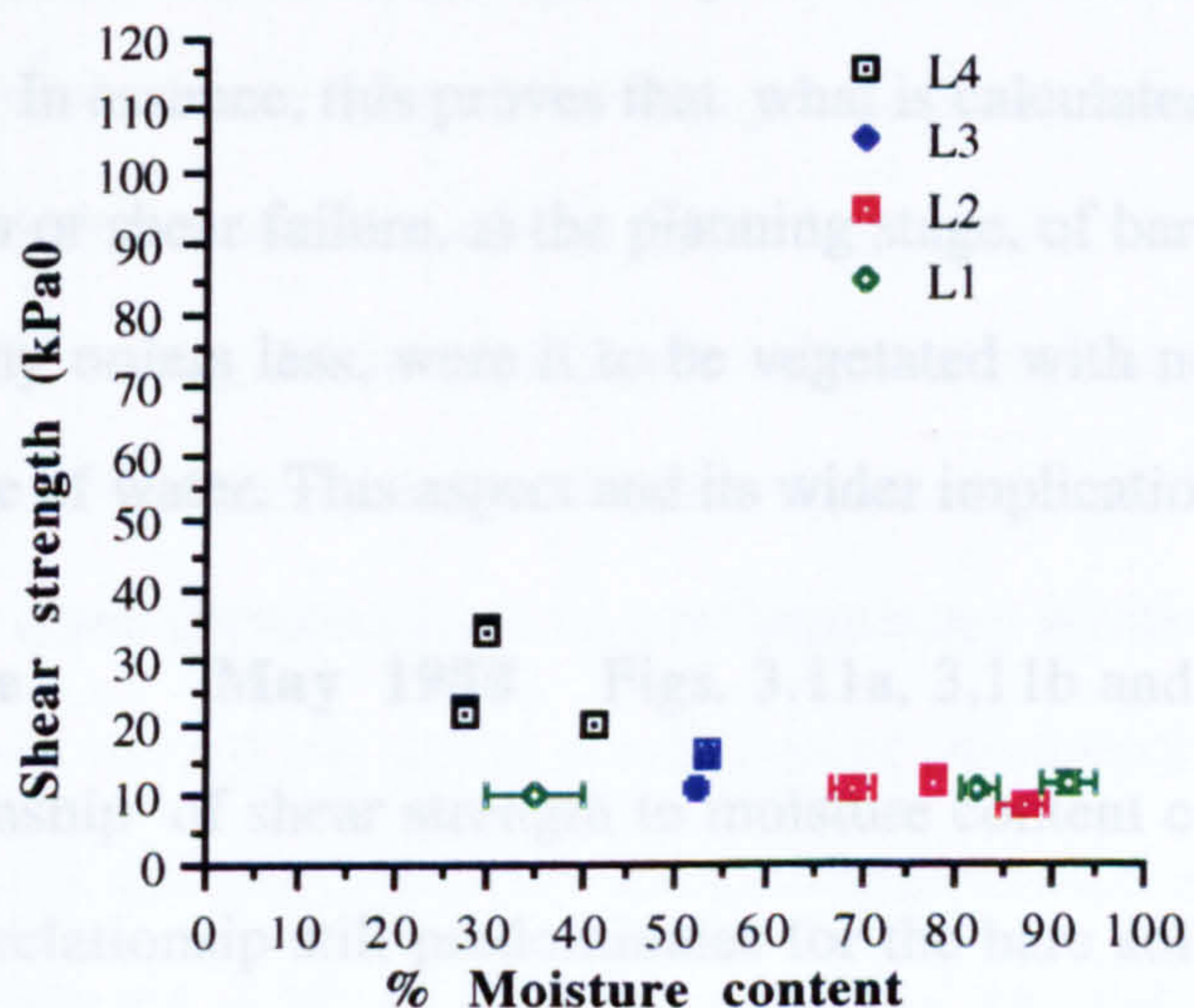


Fig. 3.10c: Shear strength Vs. Moisture content variations (February 1988)
Naturally vegetated banks dominated by *U. dioica*

The bare banks (Fig. 3.10a) in fact have a higher shear strength than the naturally vegetated banks after the prolonged flood. This is due to two reasons :

a) any top-soil which had a critical limit of failure below that needed to resist the fluvial erosive forces of a long and sustained flood had been eroded between September 1987 and February 1988. In fact the February 1988 shear strength measurements for Bare banks indicate that the layer of bank soil which was above the critical limit of failure for the maximum fluvial motive forces the banks of this reach of the River Ouzel may experience if they were left bare. By then any soil which was below these critical values had been eroded and washed away leaving exposed sub-soil of higher shear strength.

b) the naturally vegetated banks had minimal erosion (see 3.4.2a and Table 2) compared to the bare banks; but this was not due to any factor of increased shear strength imparted to the soil by the bank vegetation. In fact under long term submergence, the vegetation reduced the upper-bank shear strength and increased the moisture content of the bank (see Figs. 3.10b and 3.10c) when compared with the Bare banks. Both these would normally be proposed as contributory factors to increased erodibility of the banks (if they were bare banks). Obviously the results of erosion measurements contradict such a proposal. Therefore the inference is that even though the bank shear strength may be lowered below the normally acceptable critical limit of safety/failure, the presence of bank vegetation reduces bank erosion by a factor of as much as 7:1 (see Table 2 and 3.4.2f).

In essence, this proves that what is calculated as the critical safety limit of bank erosion or shear failure, at the planning stage, of bare banks of a hydraulic channel can be many orders less, were it to be vegetated with normal bank vegetation prior to the passage of water. This aspect and its wider implications are discussed in Ch.7.

3.4.3e May 1988 Figs. 3.11a, 3.11b and 3.11c indicate a slightly different relationship of shear strength to moisture content compared with February 1988. The linear relationship still predominates for the bare soil plot with the indication of rising shear strength in the top drier region of the bank (Level 4).

Statistically (t-test) there is no significant difference for overall shear strength values between February and May 1988 for Natural vegetation dominated by *U. dioica* ($t = -1.520$; d.f= 22; significance = 0.143; > 0.05). There is an increase in shear strength values for Level 3 of Plot 5 by May 1988 ($t = -3.796$; d.f.= 4; significance = 0.019). This region was sparsely vegetated with grasses and mixed with *U. dioica*, while Level 2 was thickly vegetated with *U. dioica*, prior to the floods. There is no significant increase in shear strength in the *E. hirsutum* dominated vegetation (Plot 3). The inference is that :

- i) *E. hirsutum* roots die under prolonged submergence and they are incapable of returning to new root production within a few months of post-submergence; It is not clear how long the adaptive mechanisms such as hollow rhizomes, will safeguard *E. hirsutum* from long-term submergence;
- ii) *U. dioica* has roots that tolerate long flood regimes which is highly questionable with its observed lack of flooding adaptations.
- iii) whether the grasses or the lower soil moisture contents contributed to the increase in shear strength values at Level 3 unclear. But, its applied implications will bear on long-term flooded waterways.

Conclusions

- i) long-term winter submergence associated with continuous long-term saturation of the upper banks lowers the shear strength of the Bare and naturally vegetated banks; such lowered values persist over the following months;
- ii) the lowering of shear strength values cannot be attributed to increases in moisture content of the banks as the measurements were carried out on sunny days with at least two to three previous days of continuous dry weather; In essence these measurements were not carried out under conditions of precipitation or bank saturation. There is no significant difference between the moisture contents of February and May 1988 for Plot 5 ($t = 0.630$; d.f. = 21; significance = 0.535). An explanation should be sought as to what changes the bank soil undergoes in relation to other physical properties such as bulk

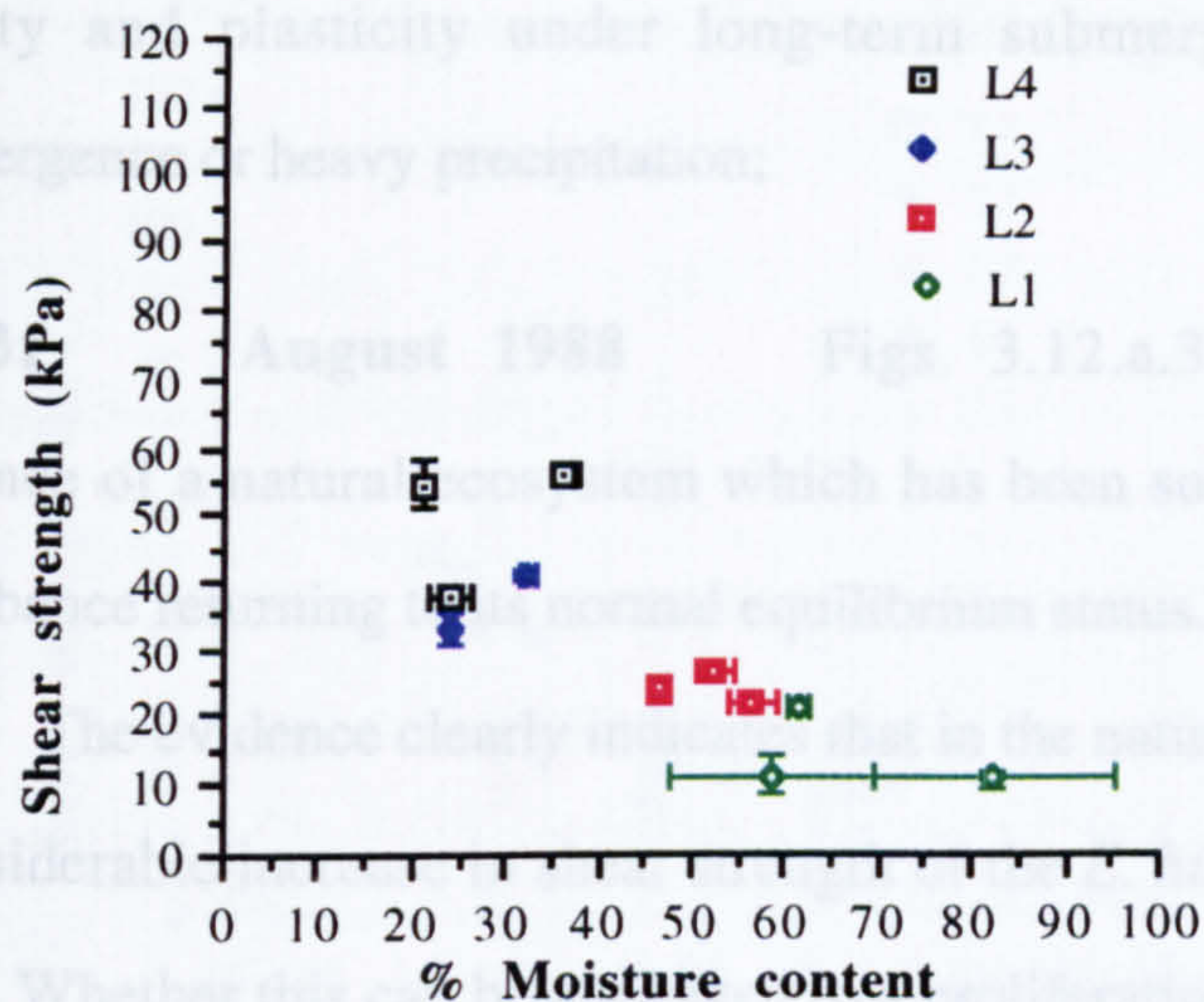


Fig. 3.11a: Shear strength Vs. Moisture content variations (May 1988)
Bare banks

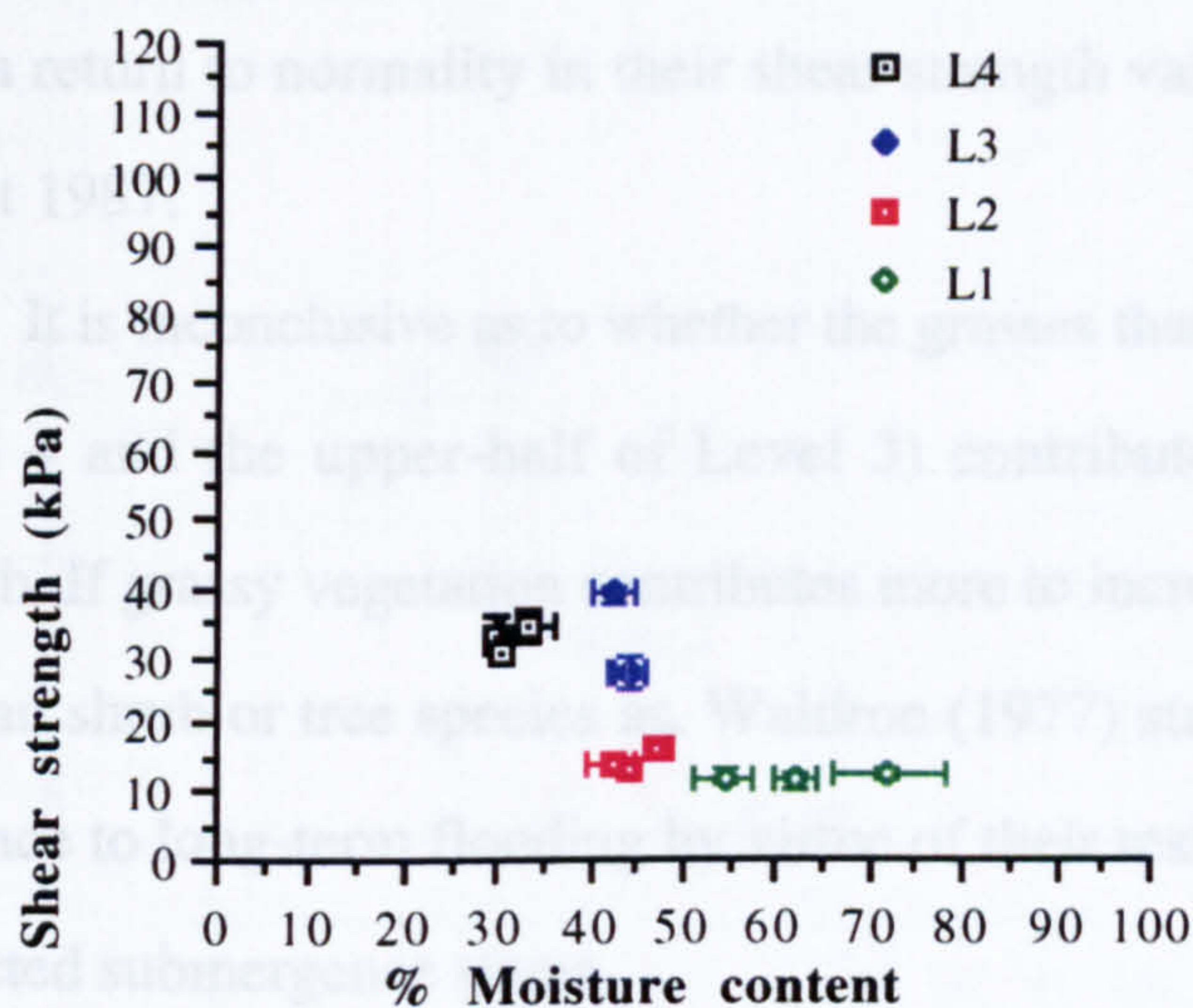


Fig. 3.11b: Shear strength Vs. Moisture content variations (May 1988)
Naturally vegetated banks dominated by *E. hirsutum* at levels 2 to 4

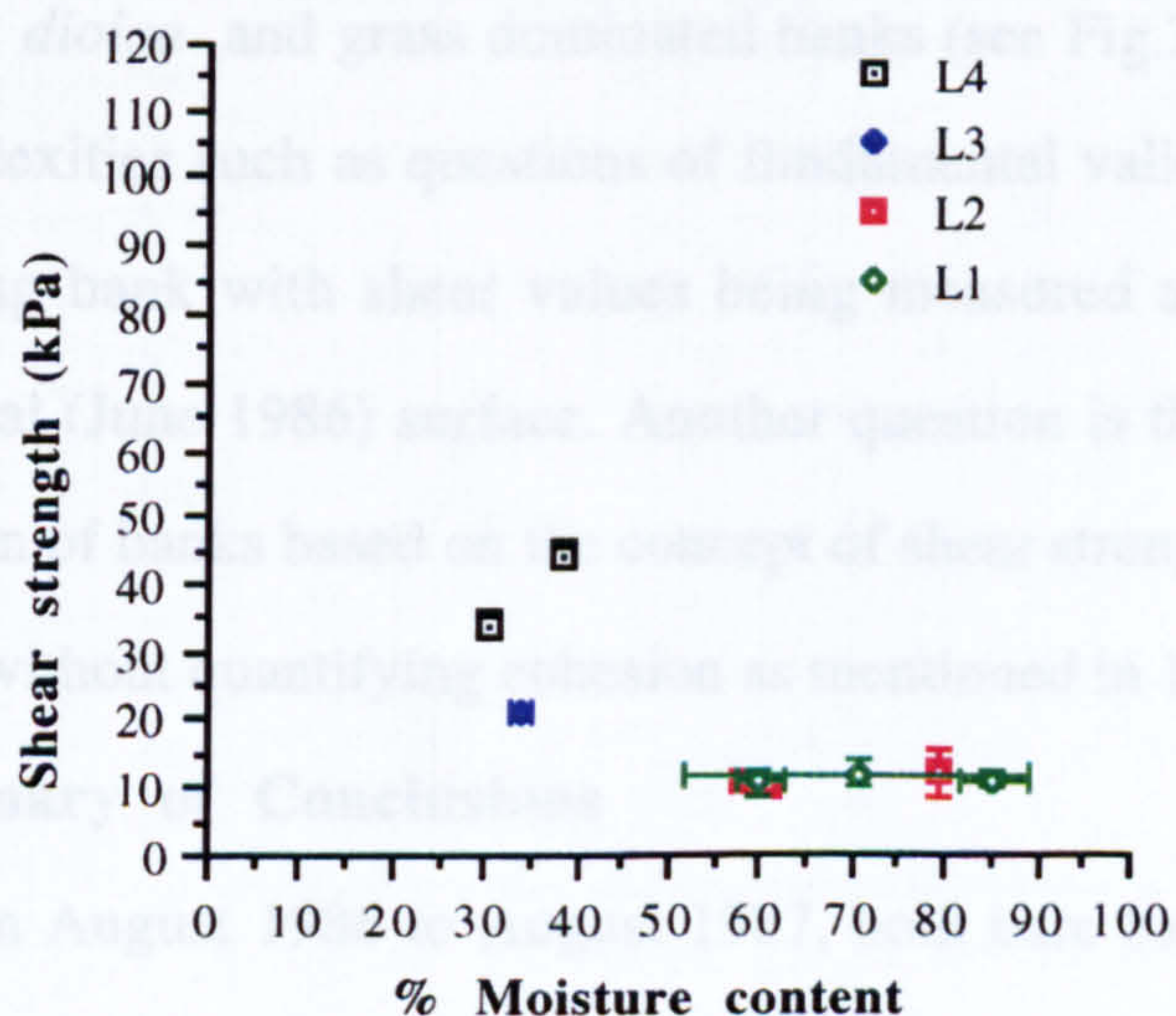


Fig. 3.11c: Shear strength Vs. Moisture content variations (May 1988)
Naturally vegetated banks dominated by *U. dioica* at levels 2 to 4

density and plasticity under long-term submergence as opposed to short term submergence or heavy precipitation;

3.4.3f August 1988 Figs. 3.12.a.3.12.b and 3.12.c present classic evidence of a natural ecosystem which has been subjected to a sudden and prolonged disturbance returning to its normal equilibrium status.

The evidence clearly indicates that in the naturally vegetated banks there has been a considerable increase in shear strength of the *E. hirsutum* dominated bank at levels 3 and 4. Whether this can be attributed to a proliferation of the root system is addressed in 3.4.4 (see Figs. 3.15b and 3.15c). Even the *U. dioica* and the grass mixture on Plot 5 show a return to normality in their shear strength values, when compared with those of August 1987.

It is inconclusive as to whether the grasses that dominated the uppermost region (Level 4 and the upper-half of Level 3) contributed more to this increase in shear strength. If grassy vegetation contributes more to increases in shear strength values of the soil than shrub or tree species as, Waldron (1977) states, then the grasses have a higher resilience to long-term flooding by virtue of their resurgent root growth consequent to a protracted submergence stress.

The values of the bare soil upper-bank are not significantly lower than those of the *U. dioica* and grass dominated banks (see Fig.3.12a to 3,12c). This leads to many complexities such as questions of fundamental validity of testing shear strength on an eroding bank with shear values being measured at ever increasing depths from the original (June 1986) surface. Another question is that of the fundamental approach to erosion of banks based on the concept of shear strength (as quantified by the hand shear vane without quantifying cohesion as mentioned in 1.5.1 and 2.3.6).

Summary of Conclusions

i. from August 1986 to August 1987, both bare banks and naturally vegetated banks show the concave curvi-linear relationship described for bare soils by other authors such as Ohu et al (1986);

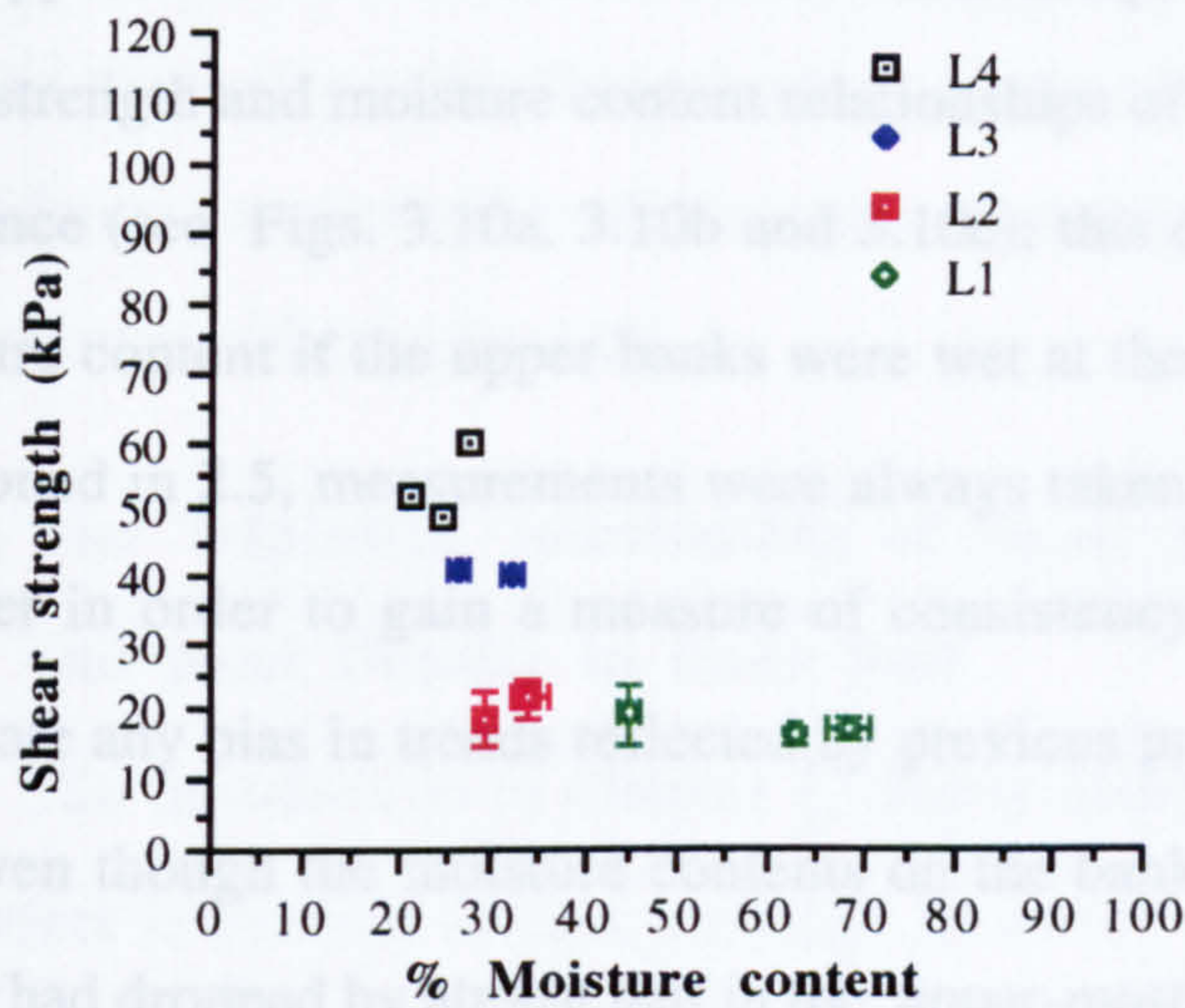


Fig. 3.12a: Shear strength Vs. Moisture content variations (August 1988)
Bare banks

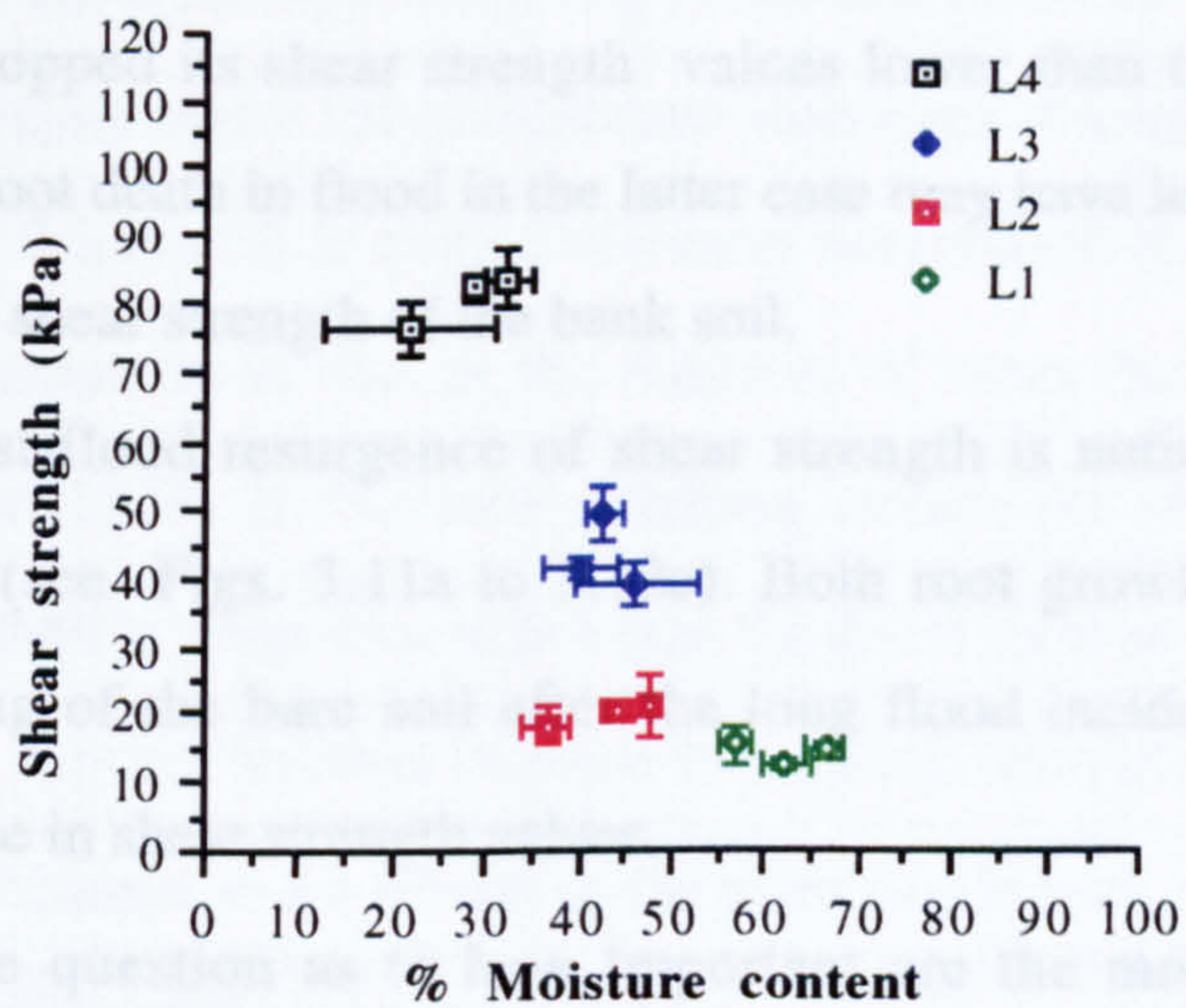


Fig. 3.12b: Shear strength Vs. Moisture content variations (August 1988)
Naturally vegetated banks dominated by U. dioica

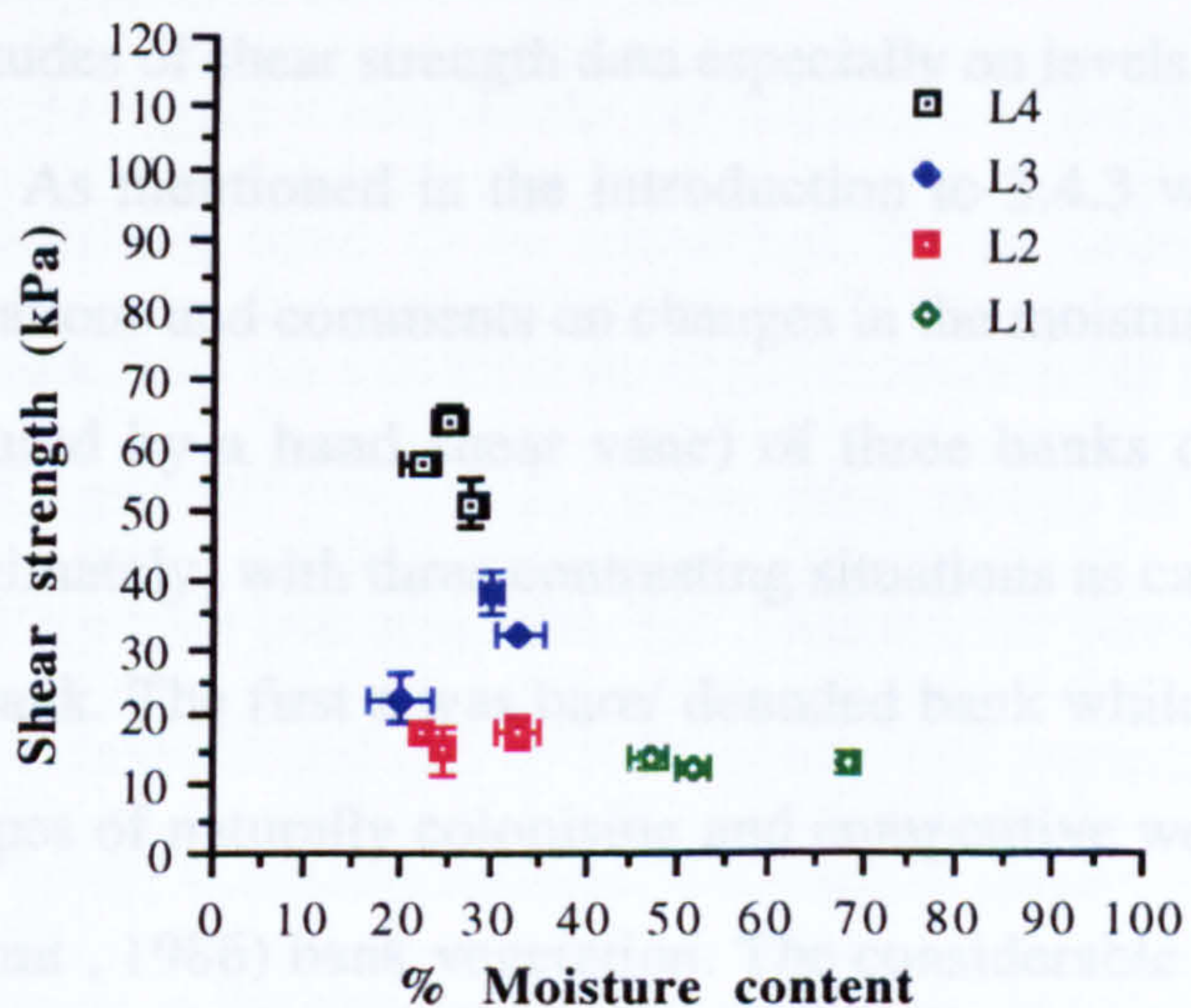


Fig. 3.12c: Shear strength and Moisture content variations (August 1988)
Naturally vegetated banks dominated by U. dioica at levels 2 to 4

ii. as opposed to the above curvi-linear relationship, there is almost total linearity of the shear strength and moisture content relationships of the banks soon after the long flood incidence (see Figs. 3.10a, 3.10b and 3.10c); this can be attributed partly to a higher moisture content if the upper banks were wet at the time of the measurements. But, as mentioned in 2.5, measurements were always taken with at least two prior days of dry weather in order to gain a measure of consistency in the weather conditions and to eliminate any bias in trends reflected by previous precipitation. What is inexplicable is that even though the moisture contents on the bank were not high, the shear strength values had dropped by almost half in the upper-most level of the banks of the river. This was the same for both bare and vegetated banks. In fact the *U. dioica* dominated banks had dropped its shear strength values lower than the bare banks. The explanation of more root death in flood in the latter case may have led to rotting roots accounting for the loss of shear strength of the bank soil.

iii. Post-flood resurgence of shear strength is noticeable in both vegetated and bare banks (see Figs. 3.11a to 3.12c). Both root growth in vegetated plots and efficient draining of the bare soil after the long flood incidence may have contributed to this increase in shear strength values.

iv. The question as to how important are the moisture content and shear strength relationships in terms of bank stability can not be addressed due to the variability of the magnitudes of shear strength data especially on levels 3 and 4.

As mentioned in the introduction to 3.4.3 what has been discussed above are observations and comments on changes in the moisture content and shear strength values (measured by a hand shear vane) of three banks of limited dimensions (5m x3.5m approximately) with three contrasting situations as can be expected on a lowland British river bank. The first a was bare/ denuded bank while the other two were dominated by two types of naturally colonising and competitive wetland preferring (Grime, Hodgson and Hunt , 1986) bank vegetation. The considerable variations in shear strength values on the same bank (see August 1986, February 1988 and August 1988 for Bare banks and both types of natural vegetation) cause concern on either/both the use of a hand shear

vane for measurements and the inherent diversity of shear strength values at different levels on the bank profile. This subsidiary aspect of the thesis (erosion studies and allied comparisons constitute the main topic) as discussed above opens an area of probable research interest for the future.

3.4.4 The 'tripartite' relationship of Shear Strength, Moisture Content and Root Density in Bank Soil

The introduction in Chapter 1, clearly identifies the importance of these three parameters in relation to bank stability. However, delineating an order of priority or importance within the three parameters with respect to bank stability is a more difficult task. Is shear strength more important than moisture content or root density? Could it be root density that is more important than shear strength? How does shear strength relate to root density? It is quite a common observation that the stability of bank overhang in most instances is due to the mattress of roots that comprise much of the overhang (Thorne, 1978). In fact such overhangs denote the 'soil aggregate stability' arising out of root cohesive properties rather than the direct increase in shear strength of the soil.

It is not because increase in moisture content may enhance bank instability, but it is more crucial to the effects of the other two factors, viz :

- a) variation of shear strength ; and
- b) healthy growth of the root system.

Yet again it may be the permutations of the combined effects of two components in turn which need to be identified for an order of preference. In this instance mathematically we can have three permutations for three factors A, B, and C. They are AB, AC, and BC (see 4.5.2). Some other factors of importance are the type of foliage present (eg high leaf area ratio, leaf density), the physical composition of the bank soil in terms of sand silt and clay or bulk density and porosity.

In the following analysis emphasis is placed on the variation of shear strength and root density as the dependant factors with respect to moisture content as the independant factor. This is mainly because the whole tripartite system is governed in turn by the

temporal variation of the hydrograph of the river, precipitation and evaporation. As such the following analysis will emphasise the variations of shear strength and root density with respect to the variations of moisture content .

3.4.4a February 1988

These measurements were carried out at the cessation of the long flood incidence of the winter of 1987/88. The results are presented graphically in Figs. 3.13a ,3.13b and 3.13c. For bare soil, the theoretical expectation is one of complete absence of roots. But as shown in the graph there were a few pieces of live root. These may be roots from seedlings which are the first colonisers from seeds dispersed from propagules in the vicinity in the prior autumn. However, these are insignificant in density on the soil to have effects on the shear strength of the bank.

The facts of significance are :

For bare soil

- i) the shear strength varies between 15 and 45 kPa.
- ii) the moisture content varies between 10 and 75 %. Beyond a moisture content of 40 % the shear strength recedes to below 20kPa.

For natural vegetation dominated with *E. hirsutum* (Fig.3.14b)

- i) the shear strength varies in the same range as that for bare soil, between 10 to 40kPa;
- ii) the root length per unit sample of soil ranges from 10 to 150cm. A simple regression analysis indicates that there is a highly significant correlation between shear strength and root density for *E. hirsutum* dominated banks (F ratio = 33.788, Probability 0.000; coeff. of correlation = 0.878).
- iii) the moisture content does not indicate a relationship to the root density.

Even though shear strength appears to increase with root density one has to question the true validity of it due to the similarity in the shear strengths between the bare soil and this vegetated plot. The one factor of significance is that as this is late winter there will be dead roots and live roots both having an effect on the shear strength of the

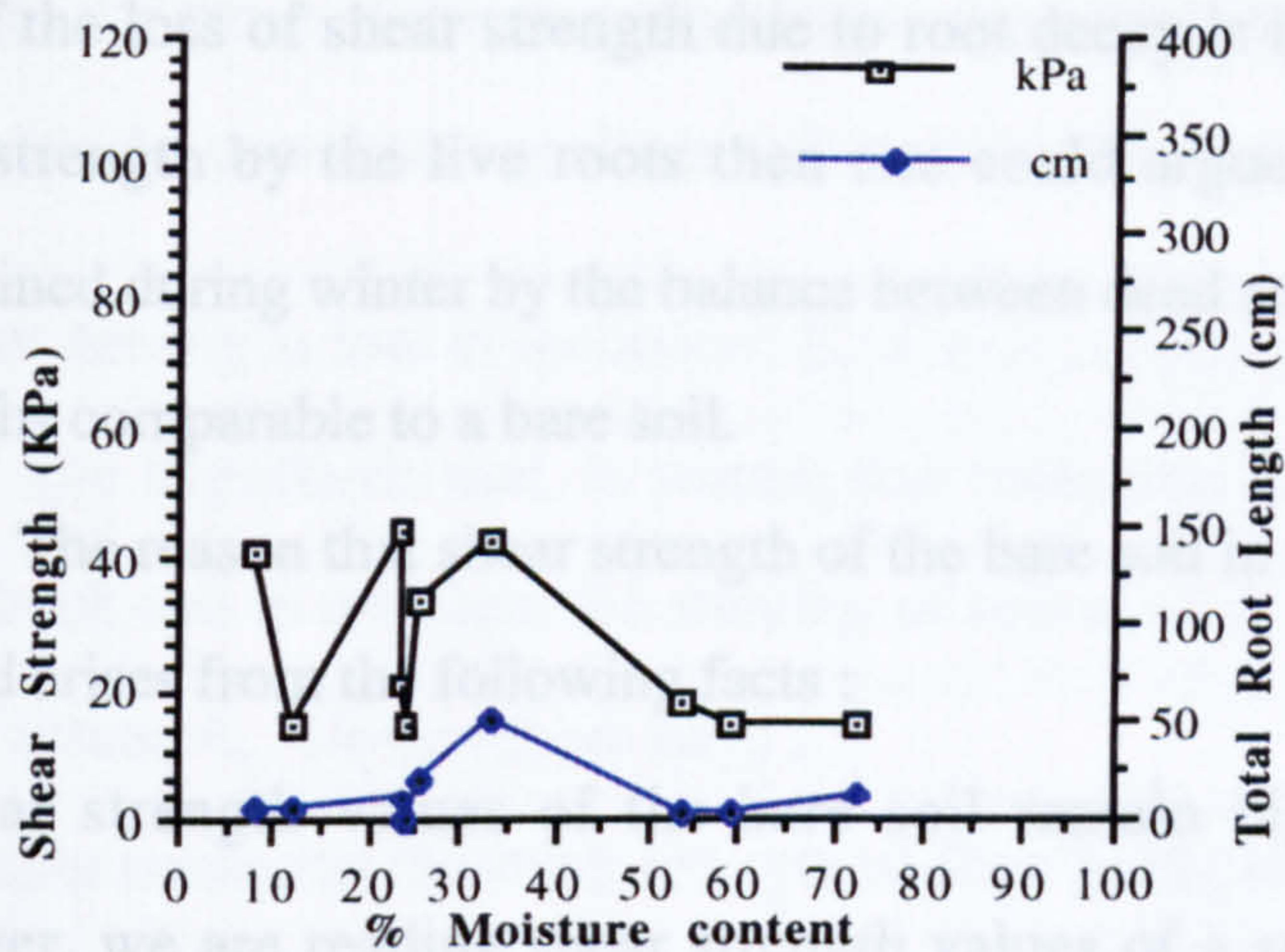


Fig.3.13a : Shear strength, Root length and Moisture content variations on the bar (February 1988) for Bare banks

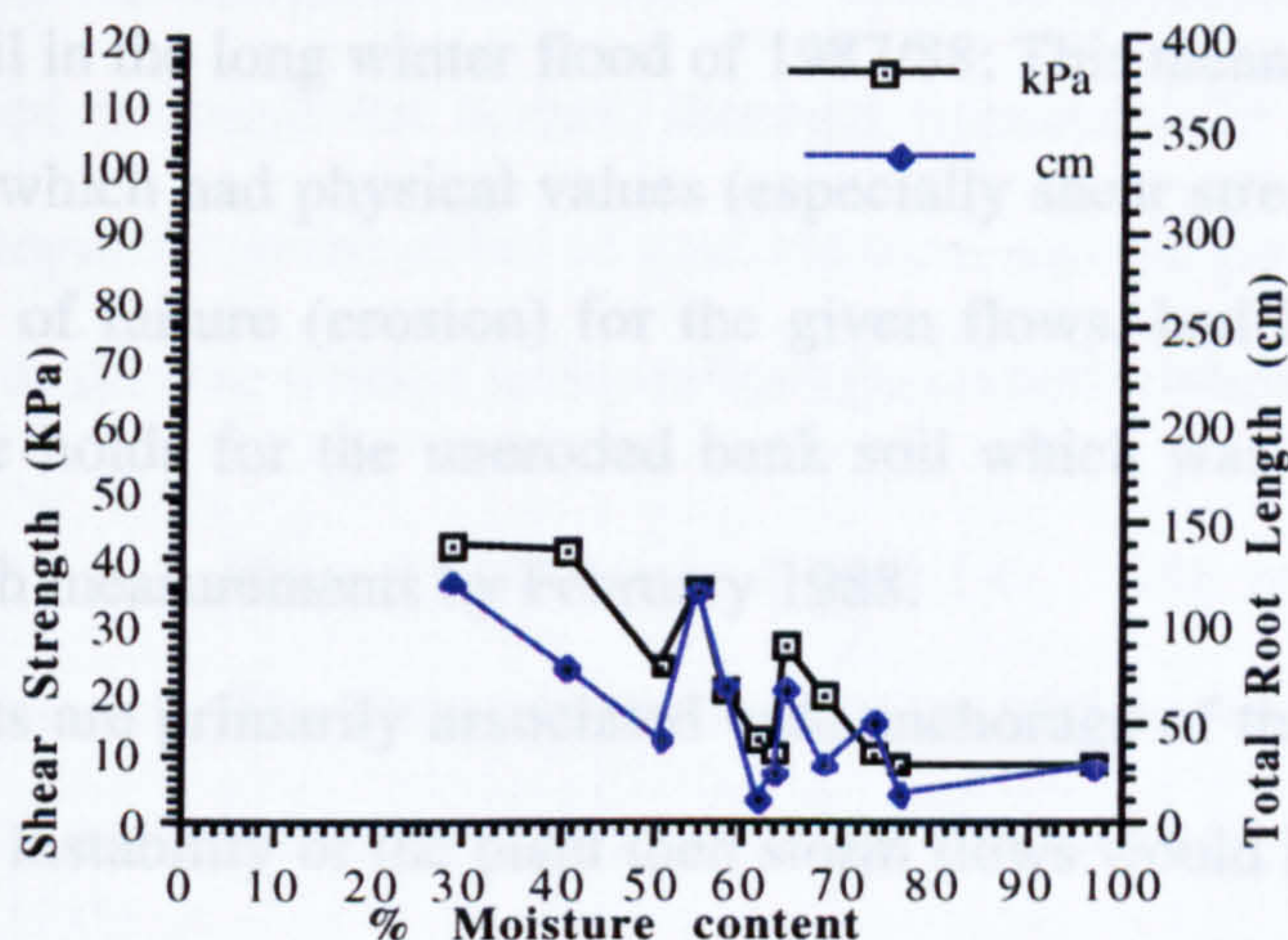


Fig.3.13b : Shear strength, Root length and moisture content variations (February 19) Natural vegetation dominated by *E. hirsutum* at levels 2 to 4;

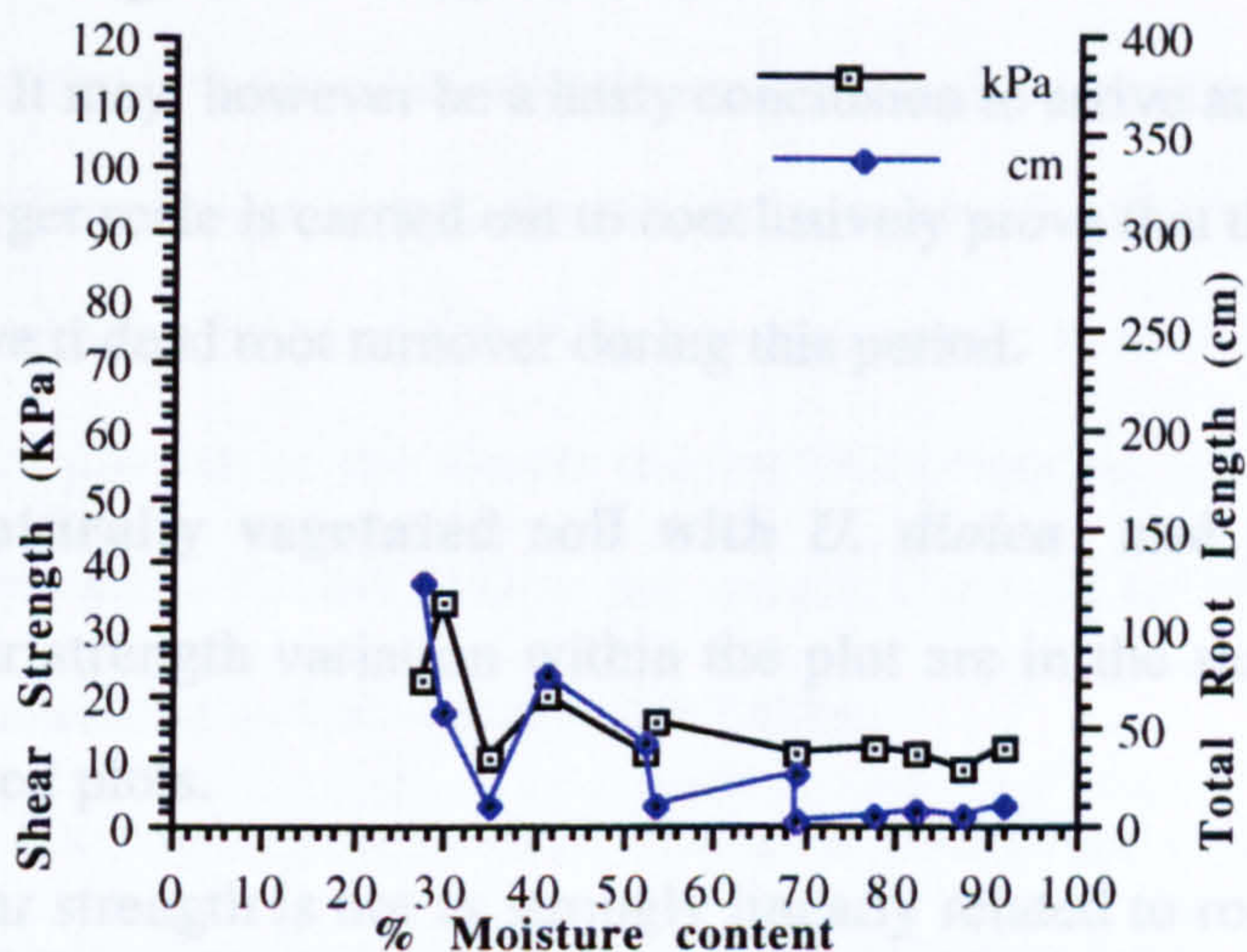


Fig. 3.13c : Shear strength, Root length and moisture content variations (February 19) Naturally vegetated banks dominated by *U.dioica* at levels 2 to 4;

soil. If the loss of shear strength due to root decay is balanced by the maintenance of shear strength by the live roots then one could argue that the stability of the soil is maintained during winter by the balance between dead and live roots to maintain the shear strengths comparable to a bare soil.

The reason that shear strength of the bare soil in this comparison should be borne in mind arises from the following facts :

a) shear strength values of the bare soil remain high for the February readings. However, we are reading shear strength values of a soil stratum which was possibly below the August 1987 level of testing because there was heavy erosion of the bare bank top-soil in the long winter flood of 1987/88; This means that all the top-soil on the bare banks which had physical values (especially shear strength) below those of the critical values of failure (erosion) for the given flows, had been washed away . Hence the reverse holds for the uneroded bank soil which was left on the banks for the shear strength measurements by February 1988.

b) roots are primarily associated with anchorage of the plant to the soil; if root death causes instability of the plant then storm flows would have shown high erosion on the vegetated plots. This did not happen (see 3.5.2a to 3.5.2e). The root system probably retained a high (live : dead) turnover ;

It may however be a hasty conclusion to arrive at unless further experimentation on a larger scale is carried out to conclusively prove that there in fact is a phenomenon of high live to dead root turnover during this period.

For naturally vegetated soil with *U. dioica* and grasses

i) Shear strength variation within the plot are in the same range as in the previously discussed plots.

ii) Shear strength is not as strongly linearly related to root length as for the *E. hirsutum* dominated plot. Analysis of variance and a simple regression analysis shows F ratio = 7.680; Probability = 0.020 and the coeff. of correlation = 0.679. The high root density

positions are those of the grass dominated uppermost layer of the bank. These may have influenced the correlation analysis as it was for the whole bank.

iii) Root density is low in the lower, *U. dioica*, dominated bank.

The hypothesis that, in winter, live roots may balance the loss of shear strength of the bank soil to maintain the stability of soil at an acceptable level may be worthy of further research. . However we have :

i) probably measured the shear strength of Bare banks at increasing depth following each period of erosion, as discussed earlier;

ii) so far investigated the effect of roots of essentially dryland plants which have occupied the bank due to their inherent 'opportunistic' invasive abilities. What may be more important is the effect of genuine semi-aquatic plants which have the physiological ability to survive winters under submergence with minimal root death.

3.4.4b May 1988 (see Figs.3.14a, 3.14b and 3.14c)

For bare soil :The shear strength variation within the plot is between 10 and 60 kPa., while the moisture content varies between 20 and 80 %. Above 40% moisture content the shear strength falls to below 20kPa. There can hardly be any effect from the negligible amount of roots present.

For natural vegetation dominated with *E. hirsutum*

The shear strength variation is between 10 and 40 kPa, while the moisture content varies between 30 and 70%. There is no increase in root density comparable with the the vigorous growth of the shoots during this period of the year. In fact, the root density varies between 10 and 150cm per sample (i.e.1.58 to 23.84cm of root per cm³ of soil) which is similar to that found in the winter.

The explanation may be that of root death and decay during the long flood which may have been so severe that post-flood growth activity was more accentuated towards shoot growth than root growth as pertinent for Spring.

For naturally vegetated soil with *U. dioica* and grasses

This type of natural vegetation on the banks shows similar root density and shear strength values as for the *E. hirsutum* dominated banks. The comments made there are equally applicable here. Overall root lengths per unit volume of soil are much less than expected for May.

Such low values pose a question on the validity of the central hypothesis (i.e. root density is related to increased shear strength of the bank and hence is critically important to bank stability).

3.4.4c August 1988 This is five to six months after the major floods of the winter of 1987/88. From an ecological aspect, the ecosystem should show signs of its ability to return to a stable but dynamic equilibrium. One of the main components of this ecosystem is the bank vegetation. As such, the success of such a return to normality should be reflected in the establishment and vigorous growth of the above ground (shoots) as well as the below ground components (roots) of the vegetation.

In this study root proliferation is measured in terms of total length of roots per unit volume of soil. Root growth is dependent on the allocation of energy by the plant depending on the time of the year/season. Spring and early Summer is associated with allocation of more energy for above ground biomass. If, on the contrary the plant diverted more stored energy for new root production during the Spring and early Summer, then the plant may have a lesser available energy allocation for shoot production. This means a reduced ability to grow more shoots which are essential for the process of maximum photosynthesis which in turn is the priority of the plant at that time of the season.

On the other hand, the imminent onset of Autumn is associated with the switching of 'source' and 'sink' relationships of the vegetation. As much as spring and early summer was associated with shoot growth to maximise the harvest of energy, the latter part of Summer is associated with diverting energy for reproductive and storage

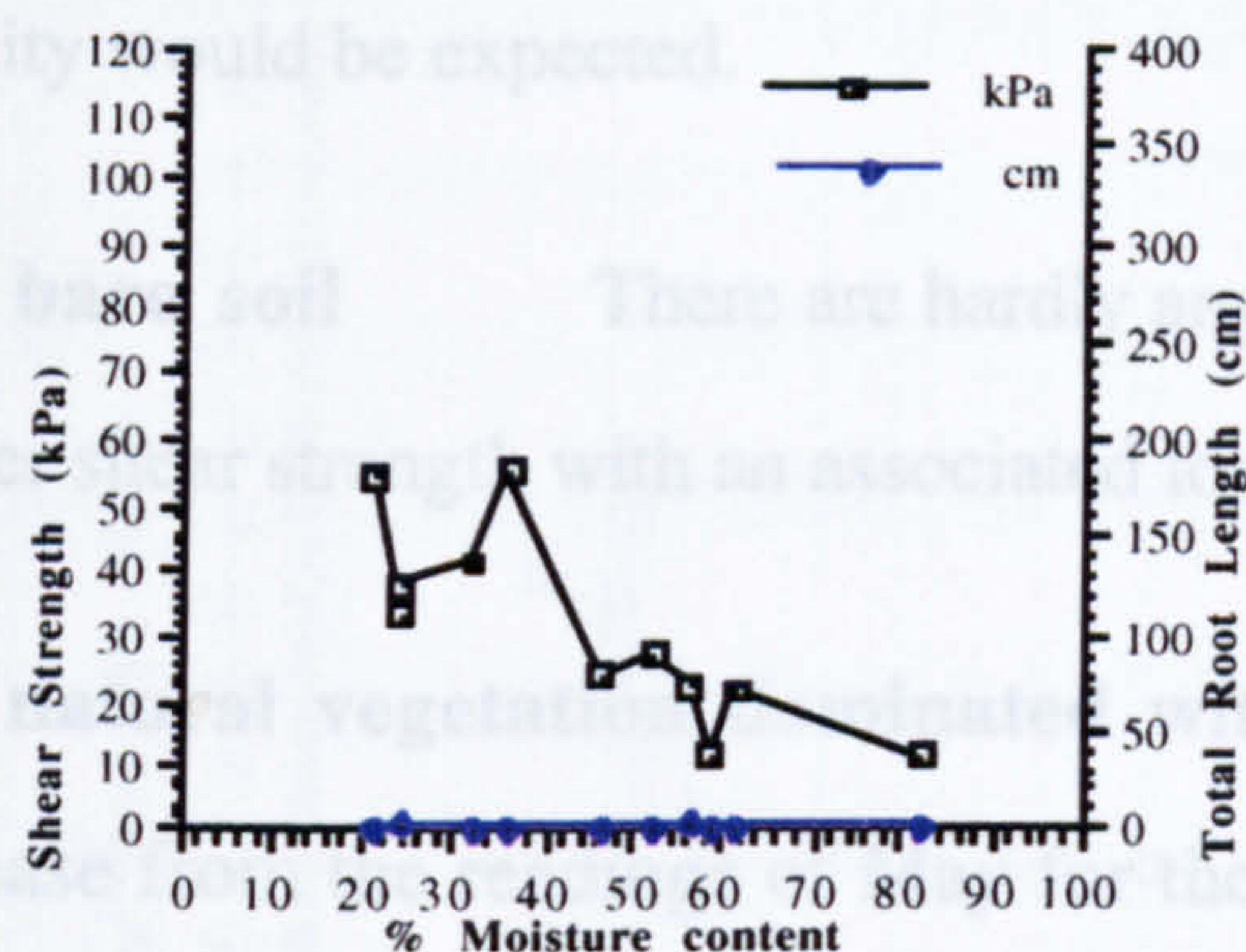


Fig. 3.14a : Shear strength, Root length and Moisture content variations (May 1981)
Bare banks;

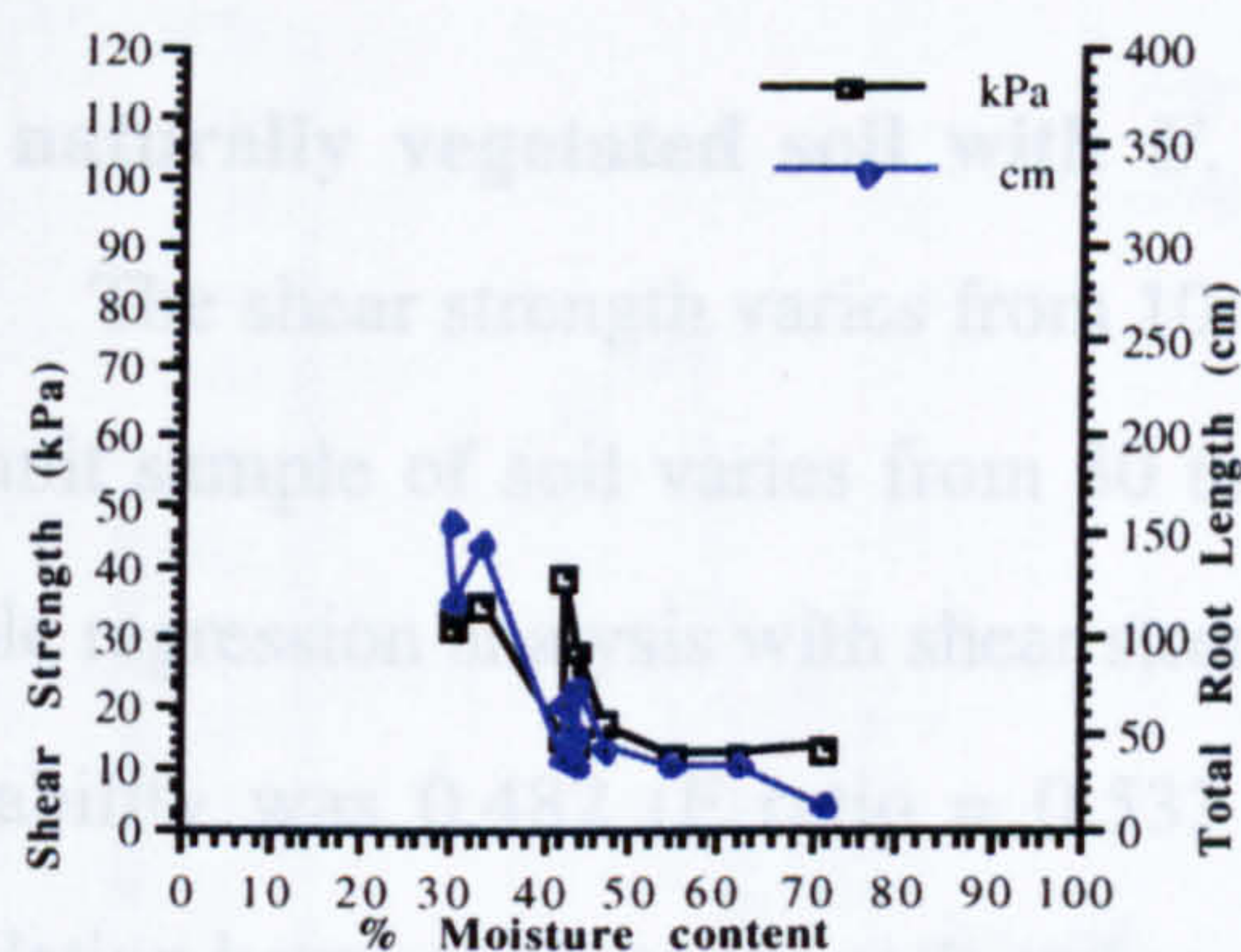


Fig. 3.14b : Shear strength, Root length and Moisture content variations (May 1981)
Naturally vegetated banks dominated by *E. hirsutum* at levels 2 to 4;

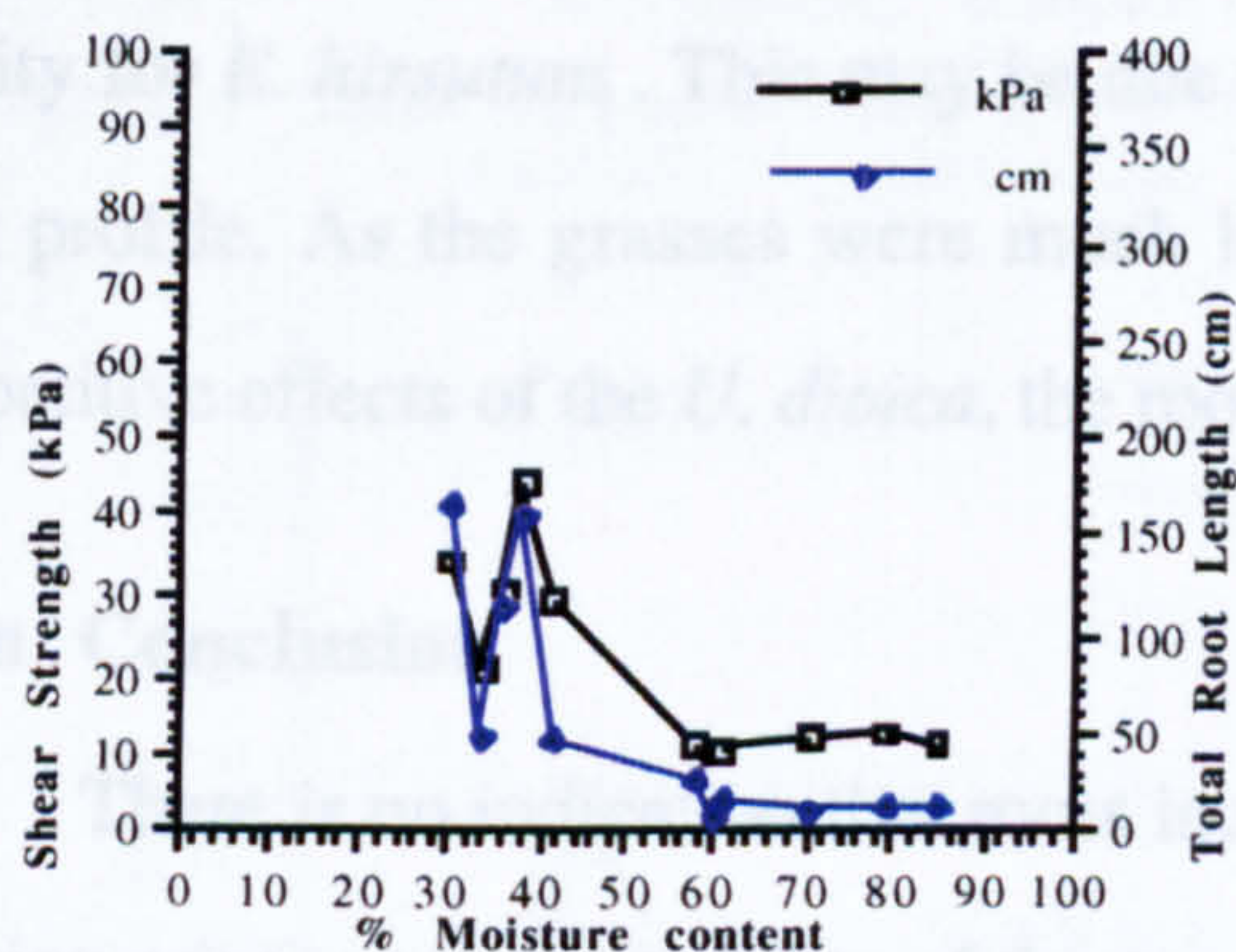


Fig. 3.14c : Shear strength, Root length and Moisture content variations (May 1981)
Naturally vegetated banks dominated by *U. dioica* at levels 2 to 4;

purposes. As roots and rhizomes play a major role in storage, increased root and rhizome density would be expected.

For bare soil There are hardly any roots in the soil as expected. There is a much higher shear strength with an associated lower moisture content for May.

For natural vegetation dominated with *E. hirsutum* There is a significant increase from the readings of May for the shear strength values of the soil. The range varies from 15 to 85kPa. There is an increase in root density too. Root length per sample varies from 40 to 150cm. The conclusion is that shear strength and live root lengths are increased over the summer, but not appreciably.

For naturally vegetated soil with *U. dioica* and grasses

The shear strength varies from 10 to 65kPa on the bank profile. The root length per unit sample of soil varies from 30 to 200cm (i.e.: 4.76 to 31.76cm per cm³). A simple regression analysis with shear strength as the dependent variable shows that the probability was 0.482 (F ratio = 0.533 and coeff. of correlation = 0.225), i.e. no correlation between shear strength and root density. A comparison with the values for the *E. hirsutum* dominated bank indicates a lower shear strength and a lower root density for *E. hirsutum*. This may be due to the grasses or the *U. dioica* or both on the bank profile. As the grasses were much less densely established, probably due to the competitive effects of the *U. dioica*, the root density may be affected.

Main Conclusion

There is no indication that roots increase the shear strength of the bank soil. The question arises as to the validity of the argument of increase of shear strength of the soil as an inherent property with the increase of root density.

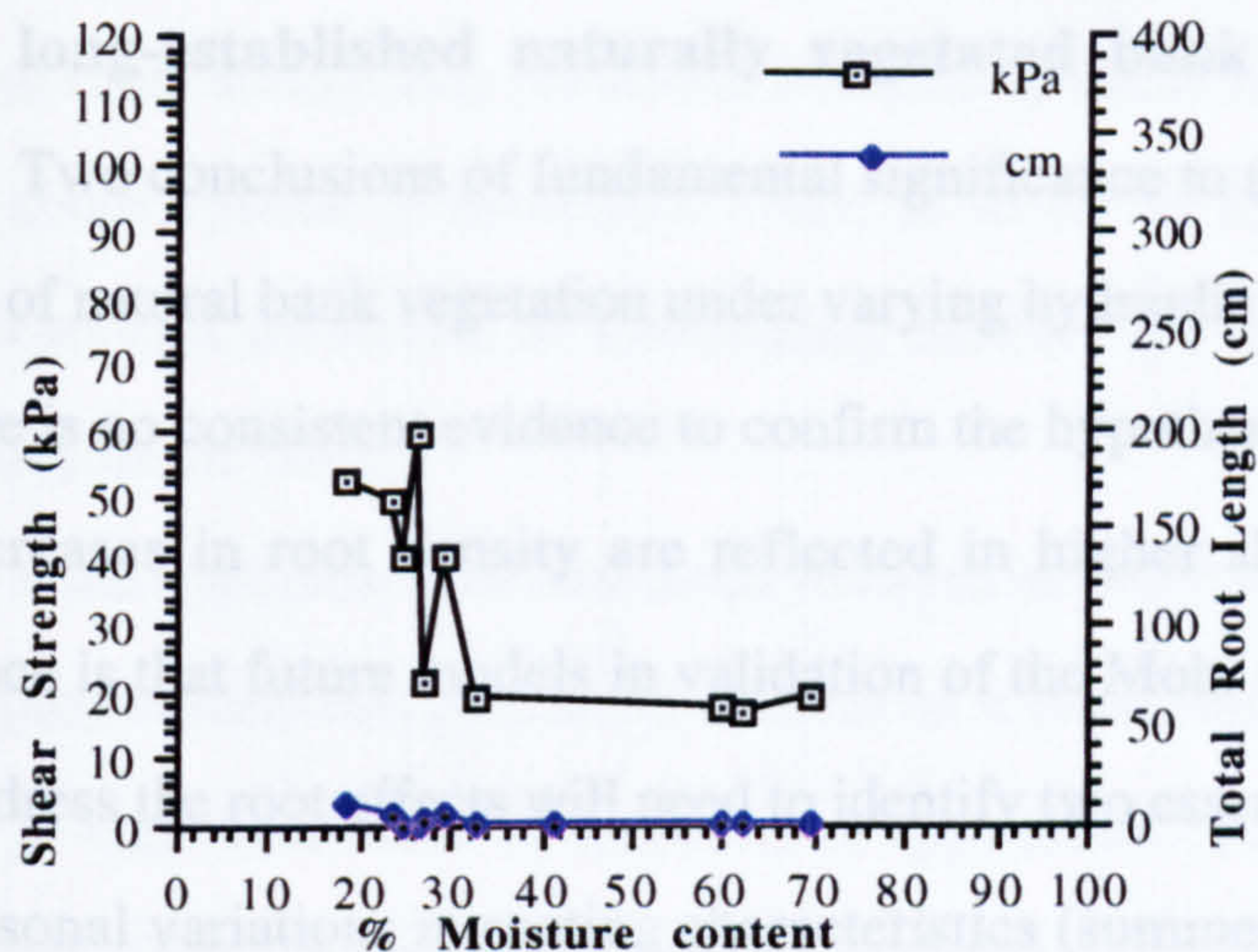


Fig. 3.15a : Shear strength, Root length and Moisture content variations (August 198) Bare banks;

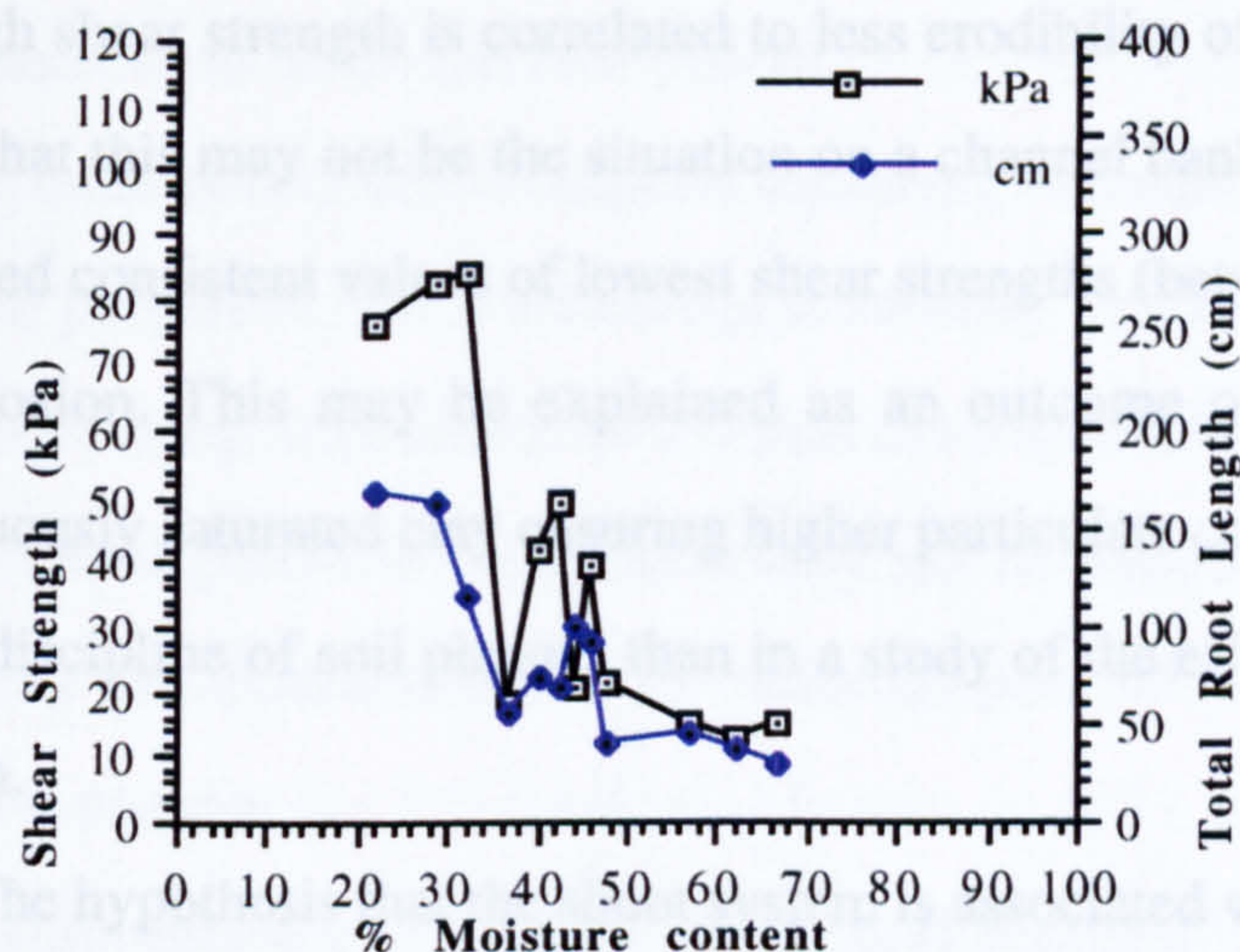


Fig. 3.15b : Shear strength, Root length and Moisture content variations (August 19) Naturally vegetated banks dominated by *E. hirsutum* at levels 2 to 4;

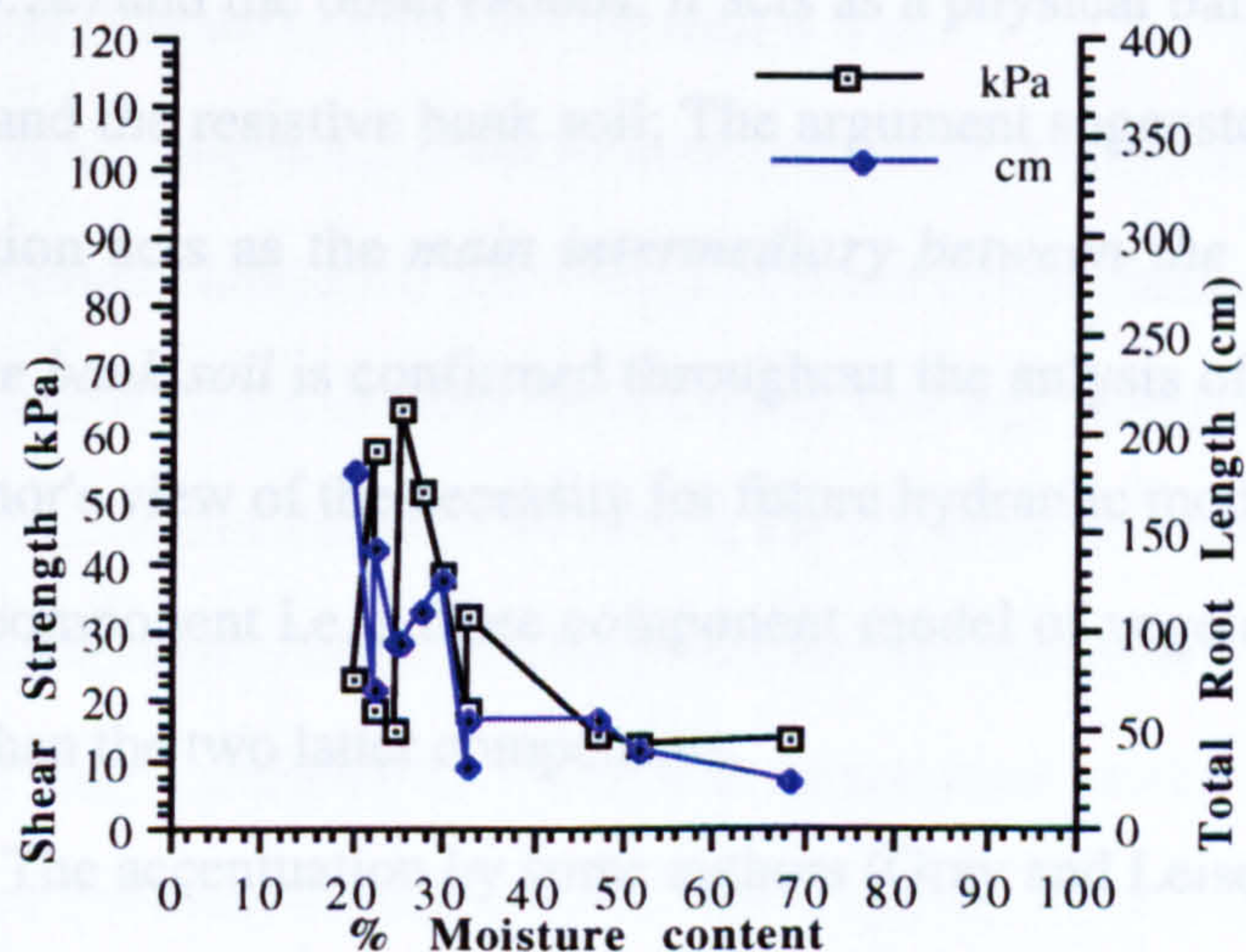


Fig. 3.15c : Shear strength, Root length and Moisture content variations (August 198) Naturally vegetated banks dominated by *U. dioica* at levels 2 to 4;

3.5 Summary of conclusions on erodibility of a newly bared bank and a long-established naturally vegetated bank

Two conclusions of fundamental significance to theoretical understanding of the effects of natural bank vegetation under varying hydraulic regimes are evident. They are:

(i) there is no consistent evidence to confirm the hypotheses that:

(a) increases in root density are reflected in higher shear strength of the soil; The inference is that future models in validation of the Mohr Coulomb or optimisations of it that address the root effects will need to identify two essentially realistic situations. They are seasonal variations in rooting characteristics (summer/winter), and a wider range of moisture contents of the soil (between dry and saturated).

(b) high shear strength is correlated to less erodibility of the soil ; it is identified in this study that this may not be the situation on a channel bank. For example, the lower bank indicated consistent values of lowest shear strengths (between 8 to 20kPa), yet relatively low erosion. This may be explained as an outcome of Van der Waal forces in the continuously saturated clay ensuring higher particulate cohesion. It is a more a challenge in the discipline of soil physics than in a study of the effects of bank vegetation on soil erosion.

(ii) a. The hypothesis that the shoot system is associated with reduced bank erodibility is confirmed as mentioned throughout the analysis of the experimental results (cf. 3.4.2a and 3.4.2e) and the observations. It acts as a physical barrier between the motive fluvial forces and the resistive bank soil; The argument suggested in 1.2.2 and 1.2.3, that bank vegetation acts as the *main intermediary between the motive fluvial forces and the resistive bank soil* is confirmed throughout the analysis of the results. This fact confirms the author's view of the necessity for future hydraulic models to incorporate vegetation as a major component i.e. a three component model of vegetation, bank soil and hydraulics rather than the two latter components.

The accentuation by some authors (Gray and Leiser, 1982) that root system is the important aspect of bank vegetation in prevention of erosion is superseded in these findings by the conclusion that priority has to be laid on shoots and not roots. However

this study accepts that high erodibility may be linked to loss of high live root density /death of roots during long periods of flooding. It has to be remembered that the presence of the shoot system is associated with, in so far as the root system is necessary to support it. This therefore, as a secondary role for the root system, may determine the erodibility of the bank.

Both hypotheses are discussed in depth in Ch. 7. Other conclusions are:

- i) the most susceptible period for erosion of a river bank is the first incidence of high discharge after denudation by a process of application of a systemic herbicide on existing vegetation ; (see 7.1 for the applied implications).
- ii) a higher mean long-term discharge causes a higher erosion of a newly denuded bank than a short-term maximum flow period;
- iii) the initial period of 3-4 months following denudation may create changes in soil physical properties which encourage erodibility by virtue of either the loss of tensile strength of dying roots and/or the creation of air spaces in the soil by decay of the roots ;
- iv) the initial period of shoot death may not necessarily lead to immediate bank soil erodibility by fluvial action; it is the secondary phase of root death period which enhances the above process;
- v) initial erosion is much higher in the upper region of bare banks than the toe-region; On the contrary for the naturally vegetated banks there was lack of fringe vegetation to prevent undercutting however minimal it was.

The possibility of an inherent aspect of 'experimental error' brought about by the erosion-pin technique in pins being covered by the falling debris from above was tested by assessment of the erosion record notes and legends (see 2.4.1); This phenomenon was limited to 3 out of the total 54 pins in the six plots in August 1986 and 2 out of 54 pins in September 1986. Thereafter the phenomenon of debris accumulation was not apparent . all field notes showed that debris accumulation covering pins was limited to the toe region of the bank during ambient flow regime, while it was not present after a period of channel inundation. Therefore the possibility of a significant error due to debris accumulation over the pin has to be discounted.

vi) During winter erosion: (see Table 2)

(a) bare banks are overall 7 times more erodible than the normally vegetated banks on this reach of this river;

(b) Upper banks are 3 to 4 times more erodible for bare banks than for normally vegetated banks;

(c) For a long-term flood, under naturally vegetated banks, the lower banks are 3 times more erodible than the upper banks;

vii) an overall curvilinear relationship of moisture content and shear strength of a river bank upwards along the bank is observed in the periods prior to the long-term flood incidence of the winter of 1987-88;

viii) long-term floods can cause considerable loss of previously high shear strengths in the upper banks of naturally vegetated banks; it is attributable to possible root death among non-semi-aquatic plants that use the bank as 'opportunistic' colonisers but lack the physiological ability to adapt to long term submergence;

ix) natural vegetation plots dominated by *Epilobium hirsutum* show signs of a higher shear strength imparted onto the soil than those with *U. dioica* and grasses. However, it is not conclusive that increased root density or other factor associated with the roots (such as tensile strength of the *Epilobium hirsutum* roots) are the reason for this.

x) for naturally vegetated banks, both live root density and the shear strength of the soil suffer a delayed period of increase in values consequent to a long period of winter submergence; The implications are discussed in Chapter 7.

xi) after a period of long submergence, *Urtica dioica* dominated banks appear to have a higher loss of live root density and shear strength than *Epilobium hirsutum* dominated banks. It is important to differentiate the significance of the loss of bank shear strength from the loss of live root density with reference to bank instability. Loss of shear strength may be due to long-term submergence rather than a drastic reduction in live roots within the bank. Under such circumstances the increased instability of the bank will be more due to loss of live roots that anchor the phyllosphere of the plant on the bank. If there are insufficient live roots to hold the above ground foliage (shoots), however

skeletal they may be, the plant will be washed away exposing the bare bank which now has an additional weakness in lower shear strength due to long-term submergence. Hence the possibility of a weak and vulnerable position prone to erosion. Such observations can enhance the opinion that 'unmanaged' bank vegetation can lead to instability of banks arising out of the presence of certain vegetation which may offer conditions that enhance bank erosion under storm flows. This is one reason that research should be directed at identifying the roles of fringe vegetation in terms of bank stability.

Chapter 4

Experiment 2 : Effects of artificial establishment of a wetland grass (*Phalaris arundinacea* L.) as a monoculture on the banks of a waterway

4.1. Introduction

The vegetation type that is mostly used by planners, hydraulics consultants and contractors as a bank lining or as a first coloniser of a newly constructed or repaired bank is grass (Hemphill and Bramley, 1989). Further technical and scientific literature on the topic have been discussed in depth in 1.4.3 and 1.4.4 earlier. Such practices cover the bank soil or other revetments mainly as an attempt to conserve the aesthetic beauty of the site or to meet the statutory obligations of the developers such as Section 11 of the Countryside Act 1968, Section 22 of the Water Act (1973), Section 48 of the Wildlife and Countryside Act of 1981 or Section 46(1) of the Control of Pollution Act 1974 (Part ii) in the British Isles and the Environment Protection Act (1990).

However, serious questions on the suitability of the choice of species from the chosen vegetation type (eg. which species of grass) have to be addressed from a spectrum of aspects of ecological significance especially in terms of adaptation to the environment. The latter aspects, as relevant to the species of plants for a given wetland habitat have been discussed in 1.4.1 earlier. A sense of healthy scepticism from an ecological point of view, on the use of grass as a canal lining may arise on the presumption that hydraulics consultants have shown limited knowledge of plant biology. This is timely in the current (Brookes, 1990) climate of conservation and ecological awareness. Identification of suitability of the species of grasses to be introduced as a fundamental component of a freshwater wetland ecosystem is highly relevant. This necessitates us to review the literature on grasses with reference to the freshwater wetland habitat.

4.1a Grasses (Family : Gramineae)

This family of plants has an almost global presence in its vast diversity of species, attributes and adaptive characteristics. Some applicable aspects of research work done by hydrologists at grass root level in its literal sense is discussed by Whitehead (1976).

From the Marram Grass (*Ammophila arenaria* L.Link) of the salty coastal dunes to the xerophytes in the deserts and the truly wetland Marsh Foxtail (*Alopecurus geniculatus* L.) or the versatile Creeping Bent (*Agrostis stolonifera* L.) with its wetland preferring subspecies (*A. stolonifera* var *palustris*) there is a considerable choice of species for different habitats. The British Isles contain in excess of a hundred species of grasses in different habitats (Clapham, Tutin and Moore, 1987). For a fuller account of the Grasses reference may be made to *Grasses* Hubbard (1984).

In the context of the use of grasses as a vegetative lining on the banks of either lotic or lentic waters, the following criteria must be met with :

- i. the service requirements (eg. prevention of bank erosion, reduction of the roughness coefficient such as Manning's N value);
- ii. suitability of the species in the given edaphic and fluvial conditions;
- iii. suitability of the species as a viable long-term component of the ecosystem (eg. niche, demography, habitat for animals etc.).

The two aspects (friction factors in grass lined canals to estimate the friction coefficient for predictive flow equations and the classification of sites as Grassy banks for the Regime Theory (Thorne et al, 1988) so far dealt with by disciplines such as civil engineering leave much room for debate in terms of ecology and plant biology.

4.1b *Phalaris arundinacea* L. Reed Canary Grass (A wetland Grass)

Habit: Stem 60 to 240cm ; leaf width 1.5cm ; spike-like panicle of 5-20cm with many rough branches; small sterile lemmas and fertile one hairy; Flowers June - August;

It is a polycarpic prennial helophyte with extensive system of creeping rhizomes .

Habitat and adaptive characteristics: A wetland species of frequent occurrence at the margins of rivers and streams, lakes, ponds and ditches, and in both shaded and unshaded mire. It has the following geographical distribution : The British Isles (100% of British vice-counties), Europe except for the Mediterranean region (85% of European territories); temperate Asia, N. America and S. Africa (Grime, Hodgson and Hunt, 1986).

McKenzie (1951) reported a high tolerance to flooding as follows : mature plants, 49 days or more, seedlings, 35-49 days, seed 35-56 days. No damage was observed

when this species was grown in pots with 25mm of water over the soil surface for three months.

For the purposes of this study *Phalaris arundinacea* L. was chosen as a wetland grass due to the above characteristics and the following additional reasons:

- i. it has been cited in literature as prevalent on the toe-region of banks of British and European waterways (Haslam, 1978) ;
- ii. it has been cited as a grass used in soil conservation projects and is popular as a species used for irrigation with sewage effluent as a pollution control measure (Marten,1985);
- iii. personal observation on surveys around lakes and river banks in Milton Keynes did indicate its regional suitability and its establishment suitability on the banks of the river where the experiments were to be carried out ; the presence of long-term established areas of virtual monoculture were evident along the Rivers Ouzel and the Ouse;
- iv. initial observations of established root systems indicated a simpler underground root and rhizome system than that of its counterpart *Phragmites australis* (Cav) Triol.ex Streudel. (Common Reed); therefore it is more suitable for aspects of quantitative sampling such as shear strength with a shear vane and root sampling with the Newman (1969) or Tennant (1975) modified technique ;
- v. establishes from seeds (Sculthorpe, 1967), transplanted seedlings or rhizome cuttings;
- vi. seeds (i.e. sexual reproduction) enhance initial establishment on new sites and vegetative reproduction (i.e. rhizomes) may contribute to long-term interspecific competitive advantages;
- vii. ability to establish on a bare bank by either sowing seeds or insertion of seedlings may alleviate the critical problem of soil disturbance associated with the process of planting rhizomes;
- viii. fast initial establishment of seedlings would contribute to early signs of any possible attributes of prevention of bank erosion and effects on variations of shear strength of the bank ;
- ix. a study that necessitated measurements of shear strength by a hand shear vane and total root length per unit volume of soil by Tennants technique in the first 18 months of

establishment of this species may not be complicated by any large organs such as rhizomes that would otherwise be found in a mature old patch of *P. arundinacea*.

x. amenity and ecological value has been proven (eg. breeding habitat for various wetland species such as swans).

xi. if the results proved to be successful *Phalaris arundinacea* could be recommended in the temperate regions of the world to remedy bank erosion.

There are possible disadvantages such as the effects of a mature rhizome system on recording shear strength values by a hand shear vane and the fact that seeds are expensive and hard to obtain.

4.2 Aims of the experiment

i. to quantify erosion of a bank which had been previously devegetated by the application of a herbicide and was in the initial process of erosion but seeded with *Phalaris arundinacea* with broadcast seeds;

ii. to compare erosion in (i) above with the rates of erosion of a bare bank, for different flow regimes that occur through the period of experimentation (25 months);

iii. to compare erosion recorded in (i) above with the respective rates of erosion of a naturally re-vegetated (i.e. mainly by seed propagule establishment and colonisation of different species as normally happens in nature), for different flow regimes that occur through the period of experimentation (25 months);

iv. to compare the respective rates of erosion of a naturally vegetated (i.e. normal vegetation as existent in other parts of the bank established over 15 years), for different flow regimes that occur through the period of experimentation (25 months);

v. to compare the rates of erosion at ambient flow under a naturally vegetated bank and under a bank seeded with *P. arundinacea* , with special reference to the corrosion in higher moisture, (toe region 0 to 0.75m from base);

vi. to compare the rates of erosion between the drier upper region in a *P. arundinacea* cultivated bank with the wet narrow band off the bank-toe region.

vii. to study the variations if any, of the shear strength of the banks seeded with *P. arundinacea* .

- viii. to study the moisture content variations on the bank profile *P. arundinacea* treatment;
- ix. to quantify the total root length per unit volume of soil on the bank profile for the *P. arundinacea* treatment ;
- x.to evaluate any possible relationships between shear strength of the bank soil with moisture content and the total root length per unit volume of bank soil;
- xi. to identify any relationships between either of the above three factors singly with the prevalent discharge of water in the river;

4.3 Materials and methods

The plots used for the experiment were: *P.arundinacea* plots : 2a, 2b, 9a, 9b, 15a, 15b; Bare soil plots : 1a, 1b, 7a, 7b 12a 12b; Naturally vegetated plots : 3a, 3b, 6a, 6b, 14a, 14b; (see Figure 2.3 for positions along the river banks.)

i. Establishment of *P.arundinacea* on the experimental plots

As the plots were devegetated in June 1986 using a systemic herbicide, an eight week period was allowed before seeding was carried out. A layer of dead vegetation was allowed to stay intact so as to form a refuge of high moisture content and darkness to enhance germination in addition to prevention of wash down of the seeds during any precipitation in the ensuing period.

In October 1986 the author proceeded to Sri Lanka for a six week pre-arranged study tour of traditional modes of irrigation canal linings and river bank repairs using vegetation. Within the 5 weeks there had been loss of top-soil due to corrasion at the toe-region and some slumping in the mid-banks. The seedlings that were established initially were considerably washed away leaving patches of seedlings on more stable soil. It was the beginning of winter and re-seeding was not an effective mode of encouraging new seedling growth. The result was that erosion of the banks continued in the winter floods of 1986 as seen in the graphs.



Plate 7. *Phalaris arundinacea* cultivated bank (Plot 2a) in August 1988



Plate 8. *Phalaris arundinacea* cultivated bank (Plot 2a/Lower bank) in August 1988
N.B. rapid colonisation of lower bank to waterline

This was followed by seeding carried out in March, May and June 1987 as described in 2.1 with the necessary arguments for such a mode of establishment. Pursuant to the re-seeding applications of March, May and June 1987, the establishment of seedlings as plants was more uniform.

However the toe region in all six plots indicated very sparse initial establishment of seedlings due to the prevalent fluctuations of the river hydrograph. By July 1988, which was the second season of growth, the toe-region plants were established and vigourously growing than the upper region colonisers (see Plates 7 and 8).

The above process is well reflected in the overall pattern in reduction of erosion with time as the establishment of the *P. arundinacea* monoculture proceeded. Mention must be made of the establishment of other species of plants that had invaded into these plots of *P. arundinacea*. They were as diverse as *E. hirsutum*, *U. dioica*, *Hypochoeris radicata* L. (Common Cat's Ear), *Cirsium arvense* (L.) Scop. (Creeping Thistle), and *Veronica beccabunga* L. (Brooklime). Throughout the experimental period hand weeding had to be carried out very carefully to eradicate these invaders. But, by mid-summer of the second season of growth it was proving a difficult proposition to hand weed the invaders without disturbing the vigourously growing *P. arundinacea* plants. As such it was limited to dates of measurement of erosion pin readings as both processes caused much disturbance to the shoots.

The methods and techniques used have been described with the appropriate reasons in 2.3. The field measurements were those of erosion, Shear Strength, Moisture Content and Root Length per unit volume of soil (see 2.3.4., 2.3.1, 2.3.2 and 2.3.3 respectively). The sampling was carried out in August 1986, February, August 1987, and February, May and August 1988.

Root length measurements were carried out in February, May and August 1988.

The laboratory measurements were mainly on two aspects:

- i. Measurement of moisture content of the labelled samples collected from the experimental plots;
- ii. Measurement of total root length per unit volume of soil from samples brought from the experimental plots ; Both procedures have been discussed 2.3.3.

4.4. Results and Analysis of Data:

4.4.1 Results: The results constitute five main sets of recordings. They were:

- a) Erosion measurements over 24 months;
 - b) Shear Strength measurements (KPa);
 - c) Moisture Content measurements (percentage)
 - d) Root length per unit volume of soil (cm/cm^3);
 - e) Daily hydraulic discharge near the site (l/s)
- (summarised data are presented in the Appendix)

4.4.2. Analysis of data

The analysis was carried out in keeping with the aims of the experiment as set out in 4.2.above.

Graphical presentation and statistical analysis: The presentation and analysis is similar to that adopted in 3.5.2 above.

4.4.2a Comparison of erosion of Bare soil versus *P.arundinacea* plots (whole banks) (Fig.4.1)

- a) Phase 1** initial period of low flow (June to December 1986; prior to establishment of *P. arundinacea*);

From June to October 1986 the mean flow ^{-d} as well as the minimum and maximum flows (Fig. 3.1a) show a consistent profile as distinct from the following nineteen months of experimentation. Initially, between June and August 1986, there was significantly higher erosion for the plots allocated for the *P. arundinacea* cultivation.

As both treatments (six plots each) were newly devegetated in June this clearly indicates that the plots intended for *P. arundinacea* were more prone to top-soil destabilisation on the application of the herbicide than those plots allocated as the continuously Bare treatment. Up to mid-August both treatments had dead vegetation covering the top soil. It was in mid-August that the dead vegetation was removed from the Bare treatment.

From August to September 1986, for the Bare plots there is increased soil erosion of almost 8-fold (see Fig.4.1) compared to the previous period, while the *P. arundinacea* plots which still had some of the dead vegetation cover has a reduced erodibility. The process of erosion was more related to the initial destabilisation of the soil by the systemic

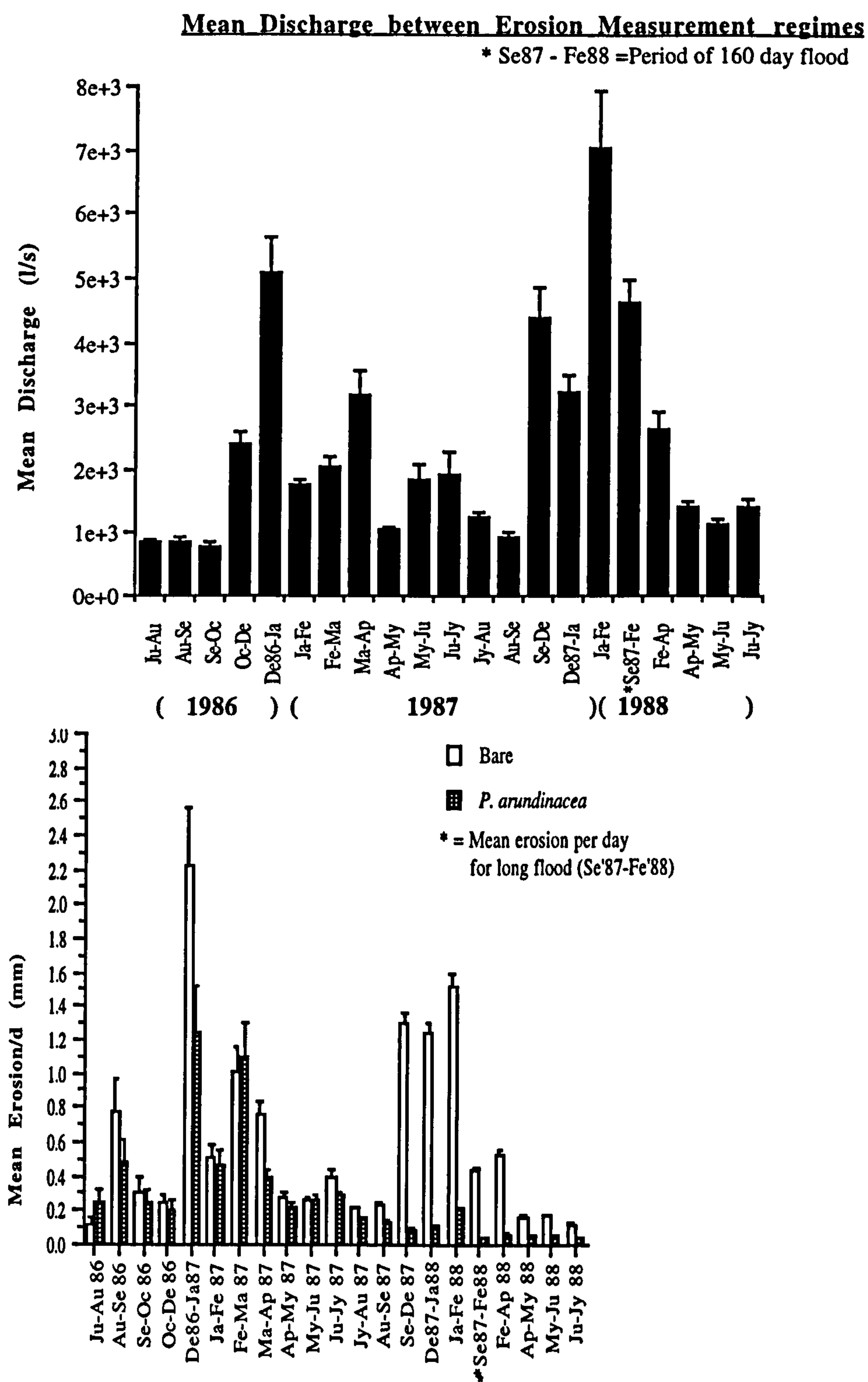


Fig. 4.1 : Comparison of Erosion : Bare soil Vs. *P. arundinacea* (Whole Banks)

herbicide treatment than any significant changes in the river flow (compare with Fig. 3a and mean discharges). In terms of rates of bank erosion, they are between 0.48mm d⁻¹ for the *P. arundinacea* seeded banks and 0.78mm d⁻¹ for the Bare soil banks.

In essence, the first 2 to 3 months were associated with the commencement of soil destability and minimal top-soil erosion together with the appearance of surficial cracks in levels 2, 3 and 4 of the banks. The following (August to September 1986) months were associated with dry-bank slumping consequent to the initiation of the process of bank destabilisation from the first three months. This process of dry-bank slumping has to be differentiated from the commonly accepted wet-bank slumping (Hooke, 1977a; Knighton, 1984). The latter is associated with bank saturation due to heavy precipitation, rise and fall of the hydrograph during flood incidence and associated fluvial forces. The former occurs in the absence of the fluvial parameters and is a result of bank destability caused in this instance by the death of the bank vegetation followed by the appearance of tension cracks (Thorne, 1978) on the top soil. This was followed by the slump which was assisted more by gravitational forces than fluvial forces.

At this stage, there is a reversal in the magnitude of erosion for the two treatments. Even though both treatments are undergoing the process of dry-bank soil slumping, the residual dead vegetation on the *P. arundinacea* seeded plots have a much reduced erodibility when compared with the recently totally denuded (bank surface cleared of dead vegetation) banks. Once the top soil (destabilised by the death of the roots) has been eroded the rates of erosion of both treatments recede as seen between September and December 1986. The above process of top soil erosion was not conducive to either the germination of the seeds or the establishment of the seedlings of *P. arundinacea* on the banks.

While it was expected that there would be heavy erosion in the first noticeable rise of the hydrograph in late November 1986, there was in fact no such erosion. It was only at the next significant rise of the hydrograph in December 1986 to January 1987 (see Phase 2 below) that these banks underwent the highest rates of erosion.

b) Phase 2 first period of winter erosion (December 1986 to April 1987);

The reasons for the remarkable increase in the rates of erosion for both treatments during December 1986 and January 1987 are :

i) the first incidence of bank-full flow in this reach of the river since the commencement of the experiments;

ii) wet-bank slumping following the first significant rise and fall of the hydrograph during November 1986;

iii) as much as Bare banks were exposed as erodible, the *P. arundinacea* plots had hardly any deep rooted seedlings or plants that could withstand the motive forces of the flow in terms of prevention of bank erosion or their own survival on the bank;

Trends of erosion on Bare banks during Phase 2 are discussed as relevant in 3.5.2b. For the *P. arundinacea* plots the reduction of the rates of erosion as compared to the Bare banks during December 1986 and January 1987 are attributed to the remaining patches of dead vegetation cover rather than any establishment of *P. arundinacea* .

During March to April 1987 reduction in rate of erosion of *P. arundinacea* banks is mainly due to upper bank establishment of *P. arundinacea* seedlings (Levels 3 and 4); There was little establishment in the lower banks.

c) Phase 3 first summer erosion within treatments (April to October 1987);

As explained in 4.3, this period was associated with three further occasions of re-seeding *P. arundinacea* plots to achieve a uniform growth of the plants. However, the unusual fluctuations of flow levels in this reach of the river (controlled by telemetry between two balancing lakes) did not allow a good establishment in the bank-toe region.

The result was that overall erosion rates for *P. arundinacea* plots are not lowered significantly (Anova : $F = 1.992$; $p = 0.884$) in comparison with the Bare banks. However, July to September 1987 was a period of rapid shoot growth and flowering of the now well rooted *P. arundinacea* plants.

d) Phase 4 a winter of early storm flows and long duration (October 1987 to April 1988); The comparison of the winter erosion in 1987/88 indicates a very significant effect of *P. arundinacea* in preventing erosion of the river banks (see Fig. 4.1, Dec 87 -Apr 88).

e) Phase 5 second summer erosion within treatments (April to August 1988).

Analysis of variance as well as the graphical differences (see Fig. 4.1) show the high significant difference between the treatments. By mid-summer of the second season it was clearly evident that this grass had established itself quite well onto the banks. The vegetation was quite dense with healthy plants reaching a height of almost two metres (see Plates 7 & 8). The plants at the base of the river bank grew more in height than the ones at the uppermost region. The significance of this is discussed later (Ch.7). In terms of negating bank erosion it appears to have fulfilled its expected suitability as a highly effective bank vegetation.

Conclusions

1. Systemic denudation not only destabilises the river banks but also creates a habitat of ephemeral relevance to seeds that germinate in the debris. The above discussion on the rates of and processes of bank erosion observed prove that bank erosion resulting from systemic herbicide denudation is independent of the hydraulics of the channel. *P. arundinacea* seedlings lack the ability to germinate and form a root system within 2-3 months. This has potential negative significance to geomorphic stability of the bank. The reasons are: (a) any high flow will uproot the seedlings thereby creating further destability of the soil (see Haslam, 1978 on critical hydraulic flows for uprooting different bank species); (b) the shoot system offers sparse bank cover; and (c) the root system offers minimal anchorage for the plants.

2. For the first summer of growth, analysis of variance of erosion between the newly colonising banks with young *P. arundinacea* and Bare banks show no significant difference (see Phase 3 above). However the graphical representation of the comparison in Fig. 4.1 shows a reduction of erosion rates for the *P. arundinacea* plots when compared with Bare banks. This lack of significance is attributed to two observations: (i). the lack of adequate ground cover by the newly emergent seedlings which have filiform, almost vertically oriented leaves (see also discussion in 5.4.2h Phase 3) ; (ii) insufficient root establishment to consolidate the top soil as in conclusion 1 above.

3. A highly significant (see Fig. 4.1) reduction of erosion of the *P. arundinacea* plots was observed during the extended flooded winter of 1987/88. The observation of a thick

ground cover (due to foliage) during winter may be offered as a probable explanation. However, it is unjustifiable to attribute the reduction of erosion as totally due to the shoot effects because the effect of root establishment can not be discussed in the absence of relevant data. Root density studies were commenced only in 1988. A future study should address the relative merits of shoot/root systems of *P. arundinacea* from seedlings to maturity.

4.4.2b Comparison of whole bank erosion (*P. arundinacea* Vs Normal vegetation) (Fig.4.2)

Up to the middle of summer 1987 *P. arundinacea* was not well established in this region as mentioned in 4.4.2a . This is reflected in the high erosion rates in the first season comparable with denuded banks with dead vegetation cover. As such only Phases 4 and 5 can be treated as phases where *P. arundinacea* had any relevance to erodibility of the bank soil.

The main conclusions from this comparison are :

Phase 1 While the naturally vegetated banks have hardly any erosion, the devegetated banks are eroding as discussed in 4.4.2a;

Phase 2 It is irrelevant to compare the two treatments at this stage as the majority of the seedlings of *P. arundinacea* which were establishing themselves were washed away by the winter floods;

Phase 3 From February to July 1987 *P. arundinacea* was not established and was not as effective as natural vegetation in negating erosion of the banks. (Anova for Phase 3 : $F = 14.489$; $p = 0.0034$); The frequent changes of the hydrograph during this period prevented both re-seeded germination and encouraged wash away of the seedlings up to July 1987. July to September 1987 is the period of active shoot growth of the *P. arundinacea* plots as mentioned earlier. From July to August 1987 establishment of young *P. arundinacea* plants is associated with a relative reduction in the rates of bank erosion (compare with the previous three periods of erosion). However, it is in August to September, when the channel flow was minimal, that it reaches low rates of erosion similar to the naturally vegetated banks. Maximum flows prior to this period (June-July, July-August 1987) as well as subsequent pre-winter period (September-October 1987)

are significantly high as shown in Fig. 3.1a. During these high flow periods there has been more erosion in the *P. arundinacea* plots than the Normally vegetated plots.

Phase 4 (October 1987 to April 1988) This is the critical test period for the newly established vegetation of *P. arundinacea* in comparison with the long established naturally vegetated banks. At the end of Phase 3 both *P. arundinacea* vegetated and naturally vegetated banks showed almost equal erodibility (see Fig. 4.2). (Anova for Phase 4 : $F = 0.725$; $p = 0.4143$);

The end of summer is associated with the commencement of phyllospheric differences between the two vegetation types. While the deciduous plants that form the major component of the naturally established vegetation undergo a reduction in leaf area ratio (L.A.R.) due to shoot senescence at Autumn, *P. arundinacea* does not lose its leaves in winter. The result is that the phyllospheres above the bank soil offer two different configurations to a stormflow. On naturally vegetated banks, species such as *Urtica dioica* and *Epilobium hirsutum* having lost their leaves form a network of dead stems standing up from the bank surface which is covered with the dead leaves fallen from above. In addition, it was noticed that these initially vertical dead stems are pushed laterally onto the leaf litter covered bank by the first storm flows. The end result is a bank covered with shoot litter which in turn is kept in position by the dead, rigid stems pressed on to them. With time the dead leaves decay leaving a ramified network of leaf skeletons with veins that form a bank surface covered with numerous sieves (see Plates 14 & 15). How far this process is significant in terms of preventing corrosion of the banks is not clear as it has not been studied. But it would be reasonable to conclude that if roots of these plants prevent the banks from slumping, then the network of dead leaves covering the bank surface and prevented from wash away by the flattened dead stems contribute significantly to prevention of corrosion of the banks.

In the case of *P. arundinacea*, the foliage does not die back. It retains its leaves which in turn flatten onto the bank surface consequent to the first stormflow. As such it forms a better ground cover than the deciduous plants.

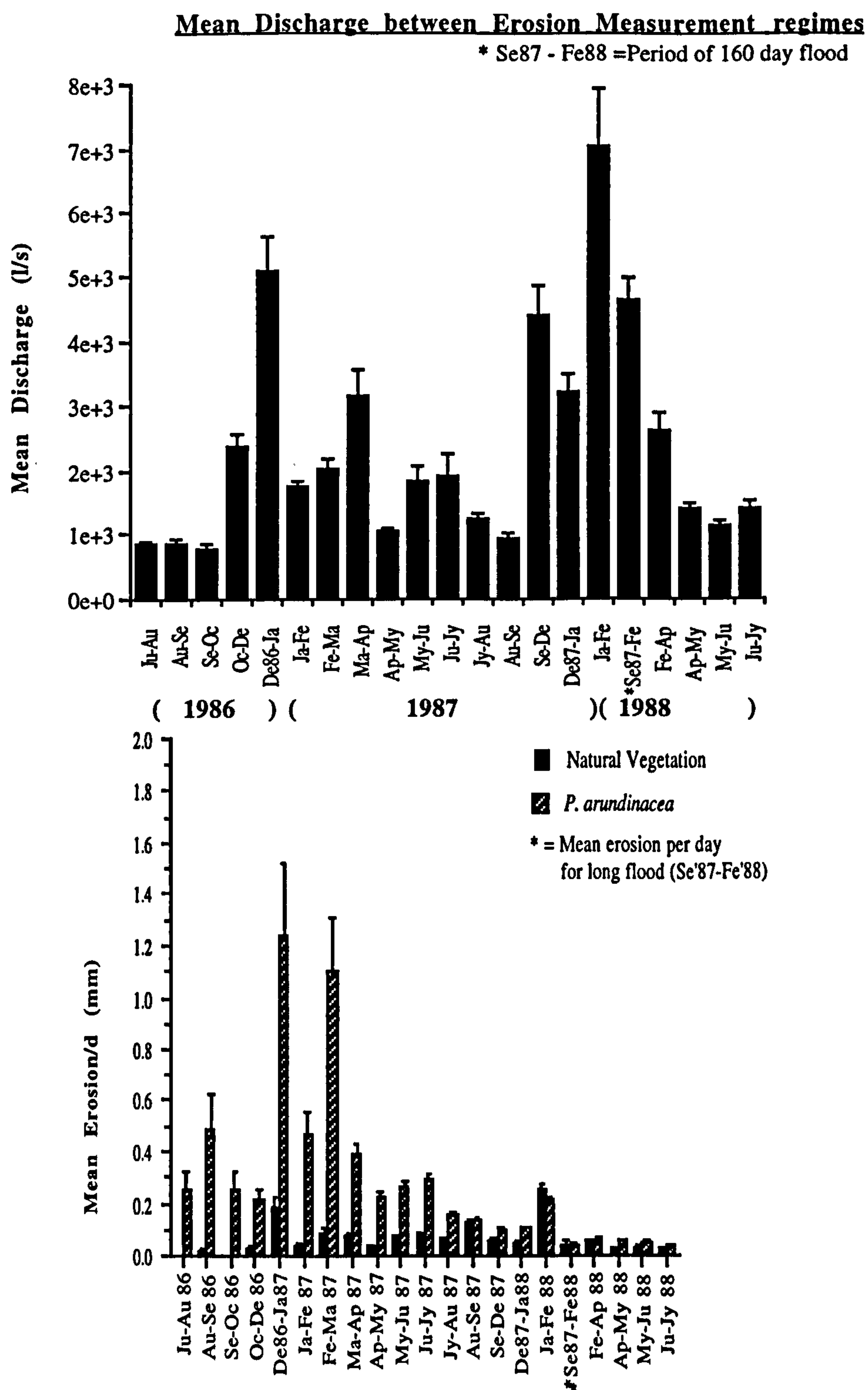


Fig. 4.2 : Comparison of erosion : *P. arundinacea* Vs. Natural Vegetation;
 (whole bank)

In terms of the data from the experiment (see Fig. 4.2) naturally vegetated banks were better at reducing erosion at the onset of the October 1987 floods and over the next

four months, upto January 1988. It must be remembered that this was an unusually early winter flood for the United Kingdom. While there was considerable senescence in the deciduous bank vegetation by the first week of October, even the fallen leaf litter had not commenced decay. Therefore it offered a better than usual protection to the banks against possible corrosion. The *P. arundinacea* cultivated banks had a good plant cover but did not reduce bank erosion as well as the naturally vegetated banks until January to February 1988.

The question arises as to why *P. arundinacea* acted as a better bank protector than naturally vegetated banks only after a three month period of frequent and almost continuous submergence. Before hastening into the virtues of *P. arundinacea* it must be noted that both treatments in this experiment show much higher rates of erosion for January to February 1988 than either September to December 1987 or December 1987 to January 1988.

In the first three months of this period the dead vegetation covering the naturally vegetated banks had decayed under longer submergence thereby exposing a higher percentage of the bank surface area to corrosion. (It has to be remembered that wet-bank slumping of the vegetated/ re-vegetated or *P. arundinacea* cultivated banks did not occur at any time during the second winter of experimentation.) In the case of *P. arundinacea* cultivated banks there was no such increase in the percentage exposure of bare banks by January 1988 because, the foliage was more resistant to decay by frequent long term submergence.

Phase 5 The second summer of growth of *P. arundinacea* shows reduction in the overall rates of erosion of the banks closely comparable to that of naturally vegetated banks. But, still this species is less efficient as a protector when compared with natural vegetation even though statistically there is no significant difference shown at 95 % confidence level. (Anova for Phase 5 : $F = 3.416$, $p = 0.0943$). A closer examination of the vegetation effects is carried out in comparisons of upper banks versus lower banks in 4.4.2c, 4.4.2f and 4.4.2g.

4.4.2c Comparison of erosion within *P. arundinacea* cultivated banks (Upper Vs. Lower banks)

a) Phases 1 and 2 The establishment of *P.arundinacea* by the seeding technique was impeded in the lower banks by fluctuating flow levels throughout the experimental period as mentioned in 4.3. As such it is clearly shown by the high rates of erosion in the toe-region (Fig. 4.3). It is not necessary to discuss the erosion in Phases 1 and 2 as there were hardly any establishment of *P.arundinacea* plants during these periods.

c) Phase 3 (April to October 1987) Initially the upper bank erosion rates are lowered with the vigorously growing grass. May to June 1977 is associated with almost equal rates of erosion between the upper and lower banks. There is an increase in the rate of erosion of the lower bank between June to July 1987.

A re-examination of the erosion data confirms this. The only explanation for the increase in erosion for the lower banks during this period is the unusually high maximum flow in the river for a summer period (see Fig.3.1a; Ju-Jy 87). Some of the young *P.arundinacea* plants at levels 1 and 2 were uprooted by the sudden high flow thereby causing the soil to be washed away in the process. This aspect of uprooting of plants by high flows and the critical flow parameters for different aquatic and semi-aquatic plants is discussed by Haslam (1978) in more detail. Her description involves not only surveys on this aspect but experiments carried out to determine the flow intensities needed to uproot well established species of wetland plants.

However re-seeding had a positive effect in prevention of further increases in erosion with the establishment of more seedlings and plants in the toe-region between July and September 1987. The low flows during this period facilitated establishment of the plant and minimised erosion at this level.

Conclusion The analysis and the discussion above indicate two factors of significance:
i. from a theoretical aspect, no specific *critical limits of stability* are identified; however, a rise in maximum flow, for the period of May to June 1987 (4450l/s) and June to July 1987 (8380l/s; see Appendix 2), indicates the range within which critical limits may be addressed; seedlings of *P. arundinacea* on the toe-region of banks weakened by previous

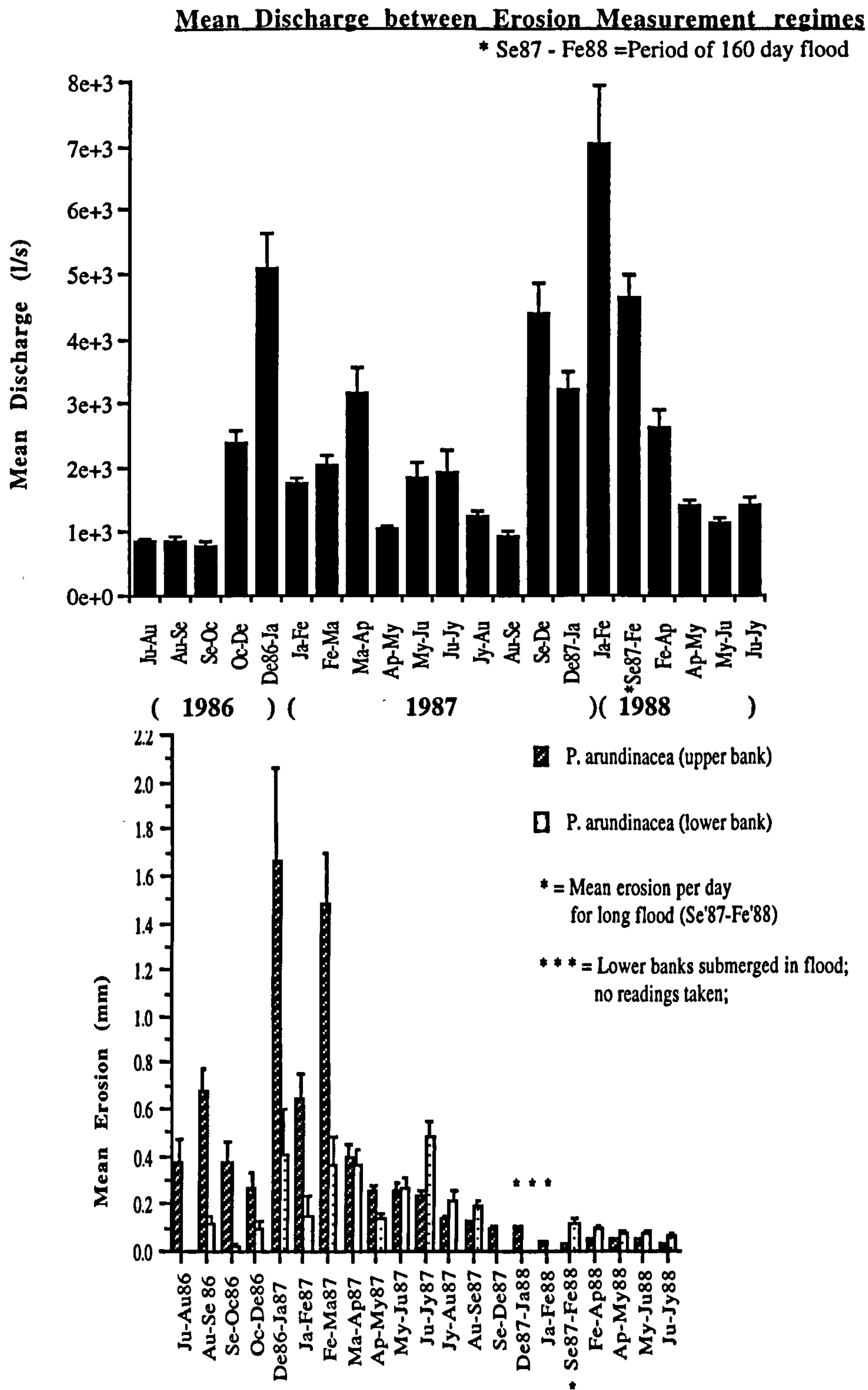


Fig. 4.3 : Comparison of erosion within P. arundinacea Banks (Upper vs. Lower Bank)

herbicide application do not guarantee effective erosion control of this region; any intermittent high summer flow is liable to uproot the seedlings;

ii. from an applied aspect, *P. arundinacea* should either be cultivated by layering of rhizomes or the channel has to be controlled at minimum flow level until the plants are well established to prevent uprooting.

d) Phase 4 (October 1987 to April 1988) a winter of early storm flows and long duration; It is not clear how the lower bank of *P. arundinacea* plots responded to the initial intensity of the flood of winter 1987/88 as no recordings of the erosion measurements could be made under submerged conditions. The mean rate of erosion of the cumulative erosion during September 1987 to February 1988 (160 days) indicates that there is a highly significant difference between the upper and lower banks (see Fig.4.3). (Anova for Phase 4 : $F = 19.021$; $p = 0.0014$). The lower banks had either offered less resistance to erosion or they had been subjected to higher fluvial erosive forces than the upper banks. The former phenomenon can arise out of lack of a well established dense plant cover during this period while the latter is possible as storm flow fluvial forces are highest at the bank-toe region (Knighton, 1984). The third alternative is that *P. arundinacea* offers a low critical limit of safety for lower bank stability in channels subjected to high flows. However, observations of naturally established mature clumps of *P. arundinacea* further up and down from the experimental area of this river showed no such signs of erosion after the same floods.

Conclusion One season of establishment and growth of this species of grass is insufficient to arrest bank-toe erosion at high flows. It is contrary to what was expected at the commencement of the experiment.

e) Phase 5 (April to August 1988). second summer erosion within treatments

The second summer is not associated with the expected total negation of the rates of erosion of the lower banks. (Anova for Phase 5 : $F = 3.69$; $p = 0.0836$). The main reason was that there was insufficient toe-region (waterline) colonisation by *P. arundinacea* in two of the six plots. In terms of rates of erosion there is no significant difference between the upper bank and the toe-region as shown above statistically.

4.4.2d Comparison of erosion of Bare soil Vs. *P.arundinacea* banks (Upper banks) (Fig. 4.4)

a) Phases 1 and 2 As mentioned in 4.4.2a, the differences in erosion rates between the two treatments at this period are due to the Bare plots being exposed while in the *P. arundinacea* plots there was an intact layer of dead vegetation left to cover the soil surface. As such erosion rates are lower until after the debris was washed away during the winter floods of 1986/7.

Conclusion

1. The process of systemic herbicide application ensures the presence of litter which is attached to the roots in the ground. This forms a protective covering to the river bank (as opposed to the bare banks). The result is reduced erosion of banks during summer floods and the initial winter floods of high intensity but short duration.

c) Phase 3 :(April to October 1987); first summer erosion within treatments

On the whole the pattern of erosion of the upper banks (see Fig. 4.4) between the two treatments are similar (Anova for Phase 3 : $F = 3.69$; $p = 0.0836$). the rates of erosion vary between May to June 1987 and June to August 1987 for the two treatments (bank types). The initial high flows (May to June 1987) result in a higher rate of erosion of the upper banks of the *P. arundinacea* assigned plots (with litter cover) when compared with the Bare banks. The subsequent inundation (June to August 1987) is associated with the reversal of the intensities of erosion for the two treatments.

Conclusion:

1. The upper region of the eroded Bare bank offers more resistance to erosion to summer floods. However, any following inundations will accelerate the rates of erosion. The first inundation lowers the inherent stability of the bank by saturation (confirms Hooke, 1977a) While this saturation may not result in immediate increase in erosion, any subsequent inundations increase the rates of erosion.

2. For *P. arundinacea* the erosion rates are lowered irrespective of the saturation by a previous inundation, due to the establishment of the seedlings and plants (see June-August 1987 in Fig. 4.4).

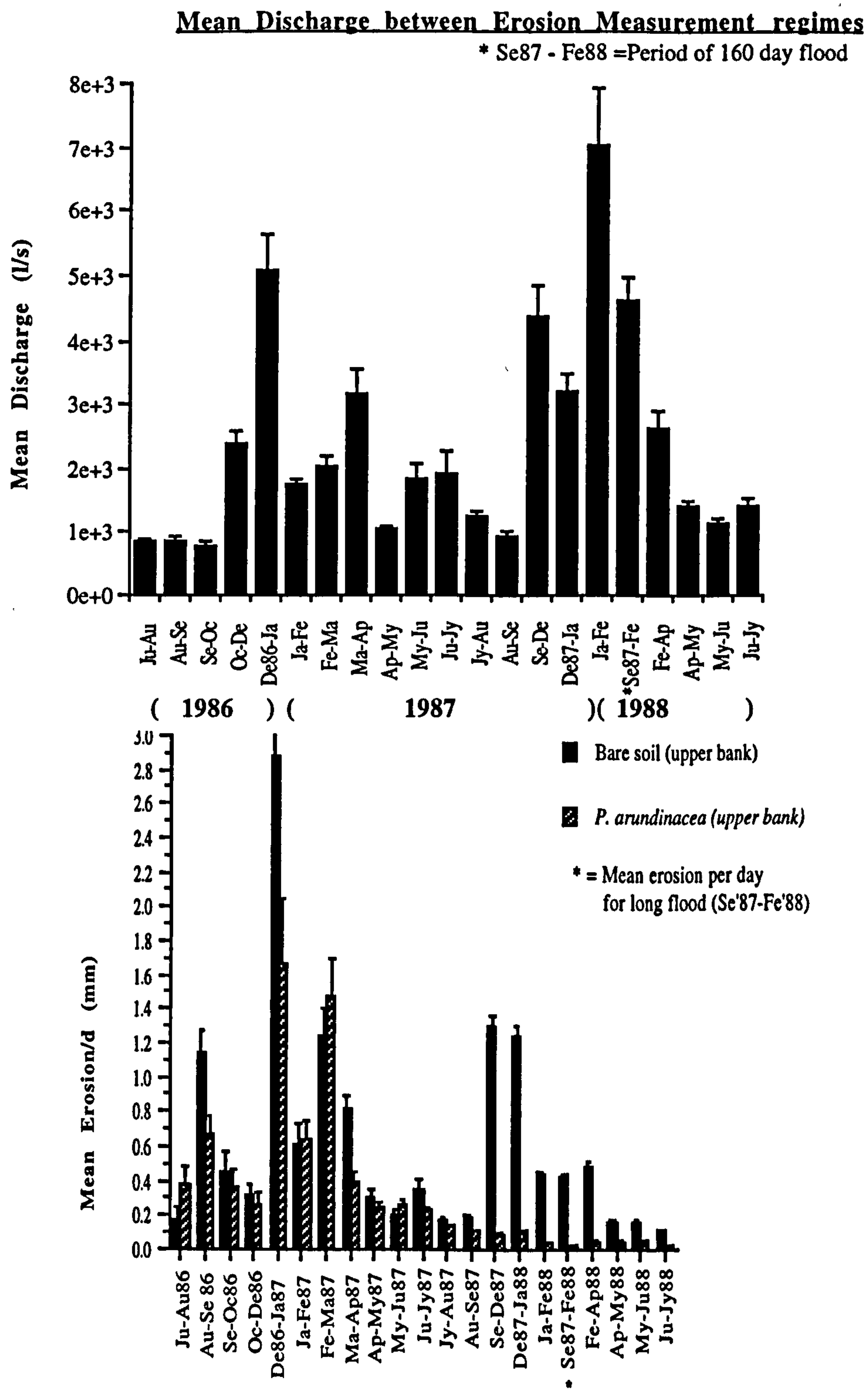


Fig. 4.4 : Comparison of Erosion : Bare Vs. P. arundinacea (Upper banks)

d) Phase 4 While upper bank erosion rates were approximately 14 times more ($1.4\text{mm}^{-\text{d}} : 0.1\text{mm}^{-\text{d}}$) for the Bare banks in comparison with the *P. arundinacea* banks in the first three months of stormflows between October 1987 and January 1988, there was a severe drop in magnitudes of erosion in the high flows of January to February 1988. But the ratio of the relative rates of erosion remained similar (approximately $0.04\text{mm}^{-\text{d}} : 0.6\text{mm}^{-\text{d}}$ for the *P. arundinacea* and Bare banks respectively).

e) Phase 5 (April to August 1988) second summer erosion within treatments;

In keeping with the expected outcome there is a significant reduction in erodibility of the upper banks in the second summer of establishment of *P. arundinacea* (Anova for Phase 5 : $F = 26.687$; $p = 4.000\text{E}-4$). However, upper bank erosion is not prevented completely by *P. arundinacea* even though by then the upper banks were well vegetated. In comparison with natural vegetation *P. arundinacea* is significantly better for prevention of erosion during this period. Fig. 4.4 and the rates of erosion (see App. 4a) demonstrate the continuing effect of devegetation as a causative factor in ongoing active erosion during a summer following a long-term submergence.

4.4.2e Comparison of erosion of Bare soil Vs. *P.arundinacea* banks (Lower banks) (Fig.4.5)

a) Phase 1 and 2 Lower bank erosion is less for *P. arundinacea* plots in Phase 2 as opposed to Phase 1. This reduction is attributed more to the dead vegetation cover left over in the *P. arundinacea* plots than to the sparse establishment of plants at this period.

c) Phase 3 (April to October 1987) summer erosion within treatments ;

The mean flow rates clearly show this summer to be associated with fluctuating water flow levels in this reach of the river. The rates of erosion generally vary depending on the flow levels prevailing. Statistically (at 95 % confidence level) there is no significant difference between erosion rates of bare banks and *P. arundinacea* cultivated banks for this Phase (Anova for Phase 3 : $F = 4.838$; $p = 0.0525$).

d) Phase 4 The inability to read the pins on Level 1 (toe-region) of the banks due to high flows is a disadvantage to analysis and discussion of the erosive processes during this period. But the mean erosion rates calculated from the cumulative erosion recorded for the 160 days of long submergence (September 1987 to February 1988) clearly

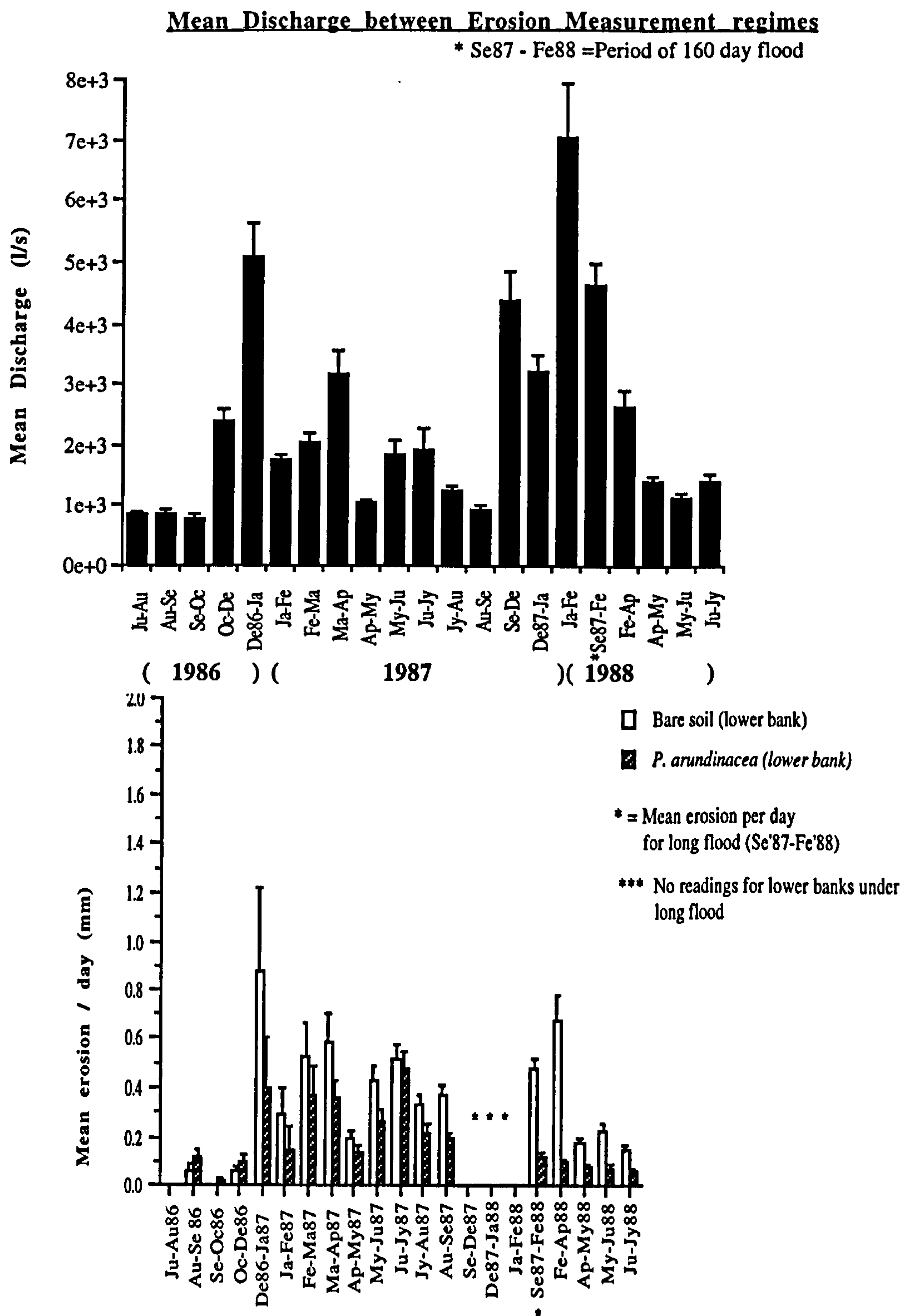


Fig. 4.5 : Comparison of Erosion: Bare soil Vs. *P. arundinacea* banks; (lower banks)

indicate that there is a highly significant reduction of erosion rates per day during this period in the *P. arundinacea* vegetated plots. It was observed that by August 1987 the *P. arundinacea* plants had not established in the toe-region as well as the upper banks. As such any credit for the reduction of erosion rates has to be allocated to the establishment of roots in the toe-region from the plants growing at level 3.

e) Phase 5 : second summer erosion within treatments (April to August 1988); *P. arundinacea* has clearly reduced the toe-region erosion rates during the second summer of its establishment. It was at this time that vegetative growth of *P. arundinacea* was noted at Level 1 (toe-region; see Plate 8). This in addition to any root effects (on soil stability) from the plants at Level 2 can/may account for the decrease in erosion rates as compared with the Bare banks during this period of the experiment.

Conclusions:

i. Seeding of *P. arundinacea* on the lower banks is initially an ineffective technique to prevent, arrest or reduce erosion. The practical implications are far reaching as this is the first and most critical stage of erosion of a channel bank under regular fluvial stress, i.e. undercutting;

ii. Once *P. arundinacea* is established in the middle region of the bank it is invasive to the toe-region within one season as seen in this study (see Plate 8). Grime et al (1986) state that *P. arundinacea* is invasive up to 0.5m into a slow flowing channel.

4.4.2f Comparison of erosion of naturally vegetated banks Vs *P. arundinacea* banks (Upper banks)

a) Phases 1 and 2 There are no effects of *P. arundinacea* as they are not established well on the upper banks (Fig.4.6).

c) Phase 3 This is the period during which there was vigorous establishment and growth of *P. arundinacea* seedlings. As such there is a clear reduction of erosion rates from June to September 1987. On a comparative basis *P. arundinacea* is inferior to natural vegetation in reducing the erosion rates. Statistically the difference is very clear. (Anova for Phase 3 : $F = 32.407$; $p = 2.0000E-4$). The reason for this is the slow initial establishment of the grass prior to the floods of 1987/88. As such no definitive conclusions may be made due to its short period of establishment during 1987.

d) **Phase 4** During this critical period we are comparing the performance of a monoculture of plants (*P. arundinacea*) that had established over the preceeding four months with that of mixed natural vegetation that had been established over the previous fifteen to twenty years. The comparison has to allow for the following factors :

Naturally Vegetated Banks	<i>P. arundinacea</i> cultivated banks
a) prevailing long-term bank stability	a) actively eroding over previous 12 months
b) factors of stability (eg. non-weathered, no drastic changes in soil properties that affect erosion rates)	b) soil porosity and bulk density may be seriously affected by artificial death of roots from herbicide application on banks
c) litter cover on banks prevent erosion	c) reduced litter due to young plants in early stages

At first (see Fig.4.6) it appears as if *P. arundinacea* is ineffective in comparison with the naturally vegetated banks in prevention of erosion during a long flood incidence. But, when we take the above factors into account it has to be concluded that *P. arundinacea* has reduced the erosion rates quite efficiently during its short establishment period. (Anova for Phase 4 : $F = 5.877$; $p = 0.0358$). Clearly there is a significant higher erosion rate under the newly establishing *P. arundinacea* vegetation when compared with the long established natural vegetation.

The more relevant test of comparison for the questions addressed in this study (*is cultivation of a monoculture better than natural re-vegetation or vice versa ?*) will be that of naturally re-vegetated banks with newly established *P. arundinacea* cultivated banks (see 5.4.2i later).

e) **Phase 5** (April to August 1988) second summer erosion within /between treatments

Statistically there is no significant difference between the long established naturally vegetated banks and the newly cultivated *P. arundinacea* banks during this summer. (Anova for Phase 5 : $F = 2.897$; $p = 0.1196$).

Graphically (see Fig. 4.6), upper bank erosion for banks seeded with *P. arundinacea* gradually reduce to the levels of normal vegetation by the end of the second season. The most critical fact is that in one season of establishment, *P. arundinacea* had not only survived a prologed incidence of flood but also consolidated the upper banks considerably.

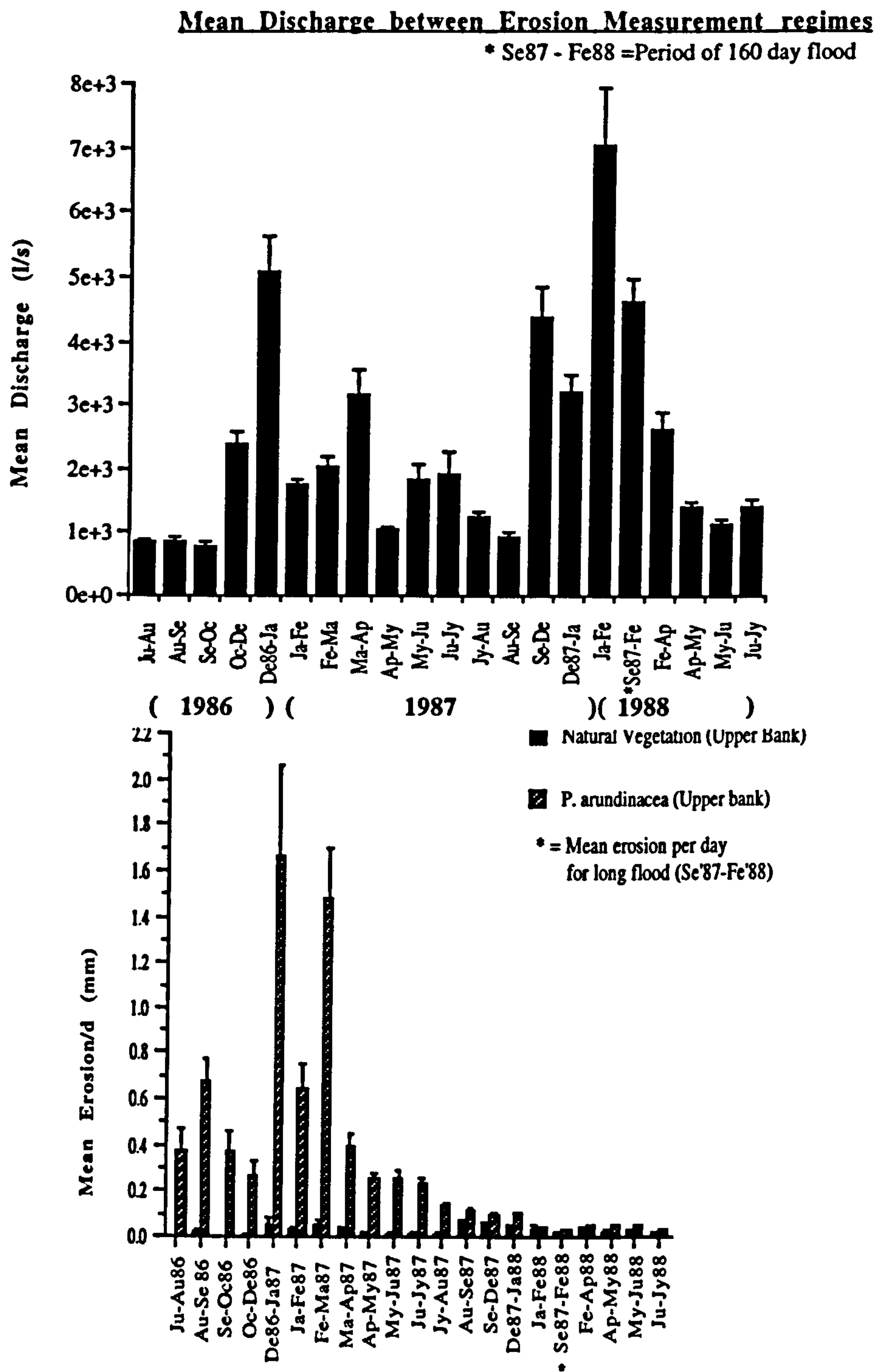


Fig.4.6 : Comparison of erosion : Natural Vegetation Vs. P. arundinacea (Upper Banks)

Conclusions:

1. The most striking feature during a critical period of prolonged winter floods (1987/88) is the reduction of erosion rates of the *P. arundinacea* vegetated upper banks when compared with the Bare eroding banks. Explanation is sought in two aspects:

i. root effects: compare the root densities of *P. arundinacea* during this period (Fig. 4.14) with root densities for Natural vegetation dominated by *E. hirsutum* (Fig. 3.13b) and *U. dioica* (Fig. 3.13c); this indicates that root densities were much the same for all three types of vegetation by February 1988. In effect, one season of *P. arundinacea* seedling establishment had contributed to a root density similar to a long established Natural vegetation on the same banks.

The conclusion is that the rooting of *P. arundinacea* contributes to bank stability in a short period of time. It must be noted that there is no overall (for all three vegetation types) consistency in the effects of roots in contributing to bank stability. The proposition is that *P. arundinacea* has a species-specific characteristic of continuous and rapid root establishment during autumn and winter.

ii. shoot effects: the main observation was that the extent of ground cover offered by young plant shoots of *P. arundinacea* during this period was sparse. However, winter die-back was minimal when compared with *U. dioica* and *E. hirsutum* dominated banks. A notable observation is that relative ground cover offered by all three types were similar during this period. A future study should address this interesting observation. Leaf area ratios at different seasons for the three species may add valuable insight to the phyllospheric effects of vegetation on bank erosion.

4.4.2g Comparison of erosion of naturally vegetated banks Vs.

***P. arundinacea* banks (Lower banks) (Fig. 4.7)**

a) Phases 1 and 2 : Lower bank erosion of *P. arundinacea* designated plots is much higher than that of the naturally vegetated banks due to the lack of establishment of the seedlings of *P. arundinacea* during this period. It has to be noted that the naturally vegetated banks had a high toe-region erosion rate (c. $0.45\text{mm}^{-\text{d}}$) during the high flows

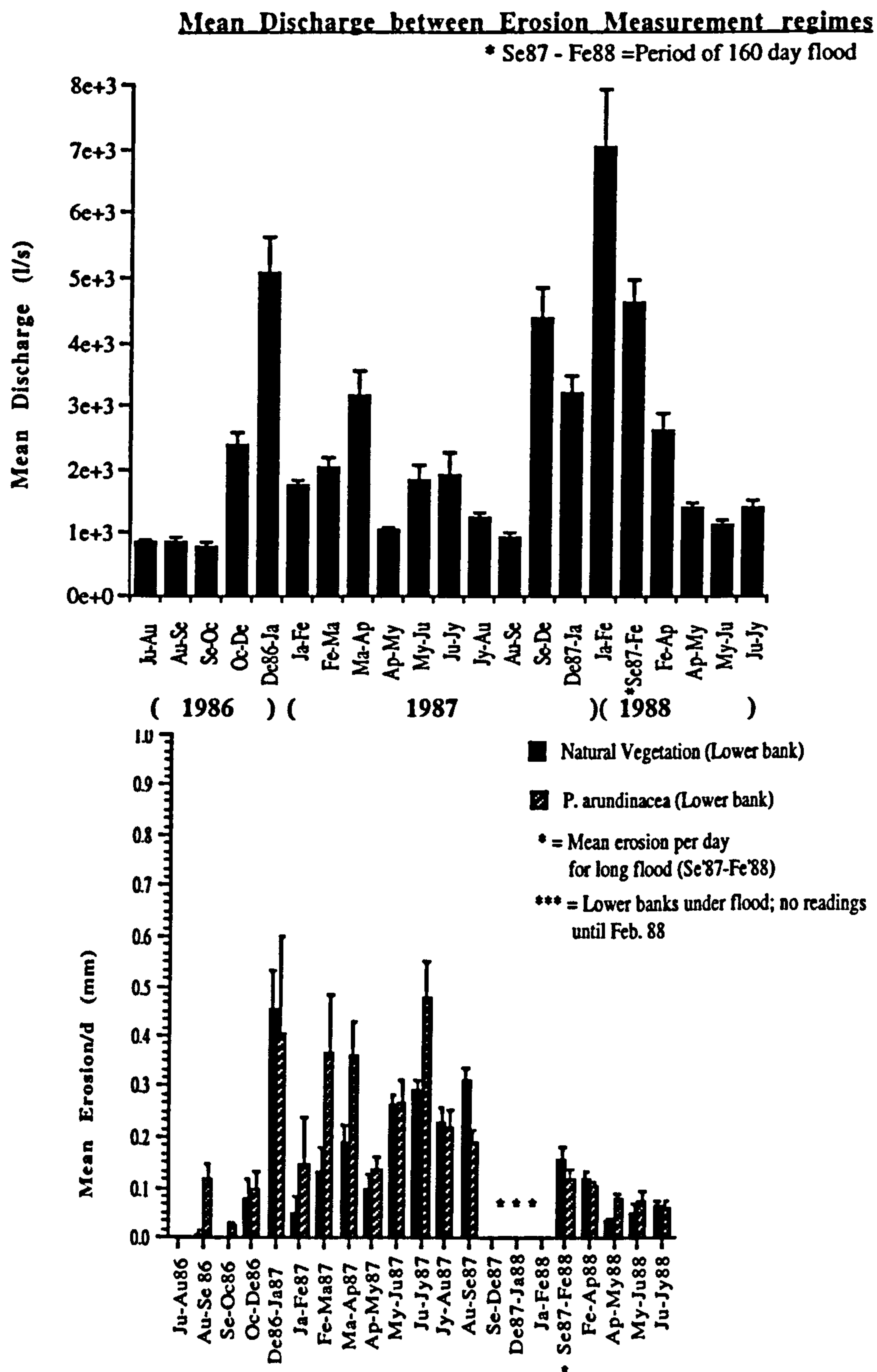


Fig. 4.7 : Comparison of Erosion: Natural vegetation Vs. P.arundinacea (Lower Banks)

of December 1986 to January 1987. However, overall magnitudes of erosion are much less when compared with actively eroding banks (see Table 2).

c) **Phase 3** (April to October 1987): The high rates of erosion of both treatments at the toe- region are due to the virtual absence of plants in this region;

d) **Phase 4** While there are no readings for short intervals (eg. Sep- Dec. 87) the mean rate of daily erosion is low for the long flood period). This does not mean that the total erosion for this period was low (see Table 2 for a comparison of Naturally vegetated versus Bare banks). It was only because the banks had yielded their maximum erodible sediment in response to the erosive fluvial forces prevalent during the whole period of 160 days between September 1987 and February 1988.

e) **Phase 5** This phase (April to August 1988) is associated with almost constant rates of minimal erosion at the toe-region of both treatments as there is establishment of *P. arundinacea* plants in most plots up to the waterline. However, the patchy toe-region colonisation on certain plots contributes to the slightly higher erosion rates of *P. arundinacea* cultivated plots when compared with the naturally vegetated plots.

Conclusions:

1. By the end of the first season of growth of *P. arundinacea* there was high erosion in the lower banks as opposed to the marked reduction in erosion of the upper banks (see Phase 3 in 4.4.2f). This is clearly due to the lack of vegetative cover in the lower banks as opposed to the increasingly dense cover in the upper banks. The vigorously growing *P. arundinacea* plants in the upper banks had no impact in reducing the erosion of the lower banks. Therefore it has to be concluded that the physical absence of vegetative cover on the lower banks exposed the lower banks to fluvial erosion.

2. The same conclusion, (i.e. absence of foliage cover acting as a barrier between the lower banks and the flowing water contributed to continuous erosion) applies to the Naturally vegetated banks. The main reason for this is the absence of semi-aquatic (fringe) species in the lower banks as shown in Plate 5.

4.5 Shear Strength, Moisture Content and Root Length Analysis

In brief, aims vii, viii, ix, x, and xi of 4.2. are addressed in the following analysis. The discussion will concentrate mostly on the changes brought about by the establishment of *P. arundinacea* as compared with the bare soil which will be considered as the primarily important 'control' treatment. Natural vegetation will be discussed in terms of observed similarities and differences with the effects of the process of establishment of *P. arundinacea*.

The analysis is carried out on four representative plots, (1a, 2a, 3a and 5a)

The time table of this measurement regime was given in Table 3.

4.5.1 Comparison of Shear Strength versus Moisture Content

August 1986

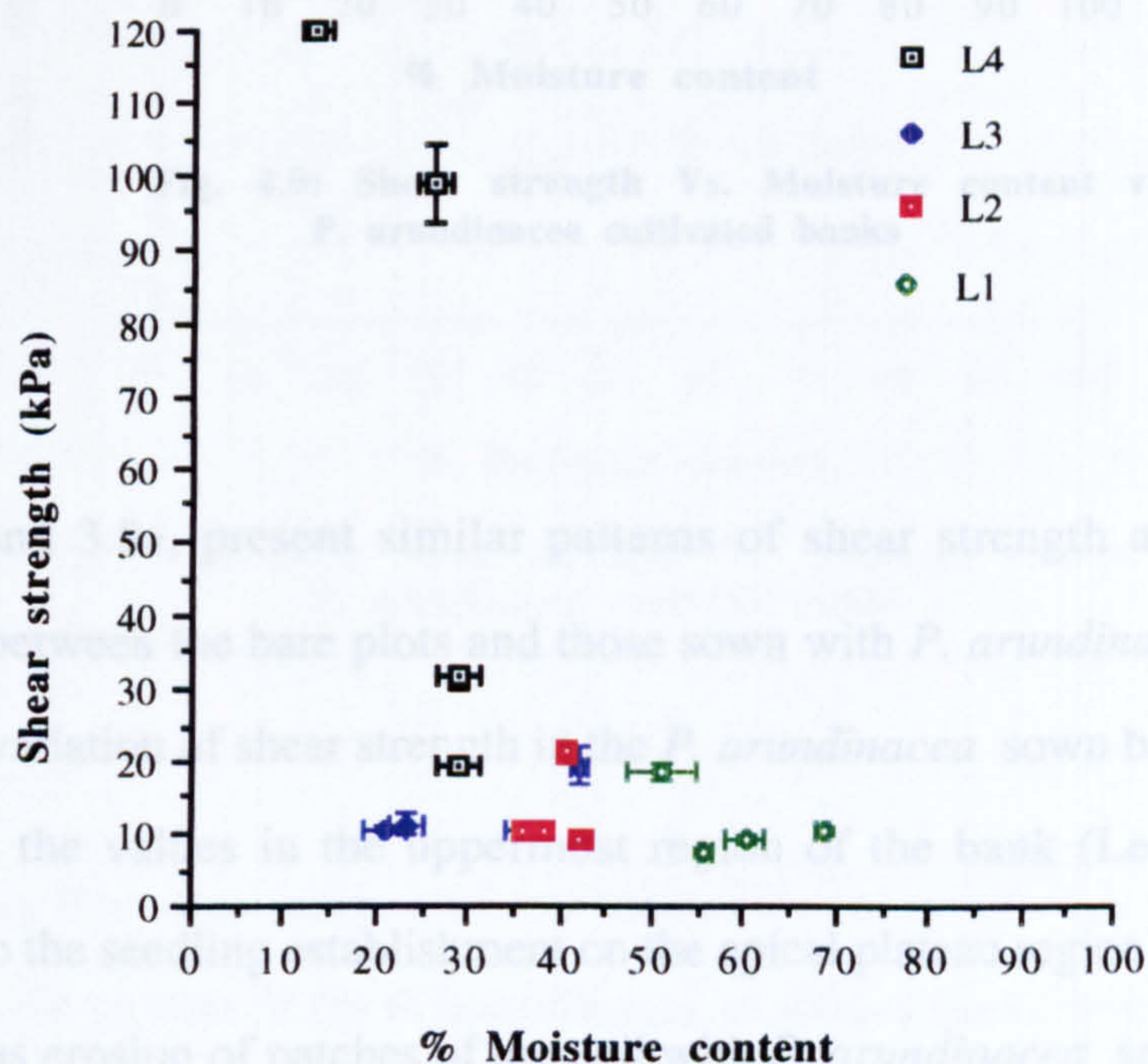


Fig. 4.8: Shear strength Vs. Moisture content variations (August 1986) *P. arundinacea* cultivated bank (6 weeks after seeding)

Figs. 4.8 and 3.7a, 3.7b, 3.7c (see: Ch.3), graphically represent the pattern of shear strength variations prevalent at the time. Except for Fig. 4.8 the implications for the others have been discussed in 3.5.3a. At this stage the seedlings of *P. arundinacea* do not have any deep roots. The shear strength of the bank is very similar to that of the bare soil banks. This is to be expected as both areas were within approximately 15m of the same bank.

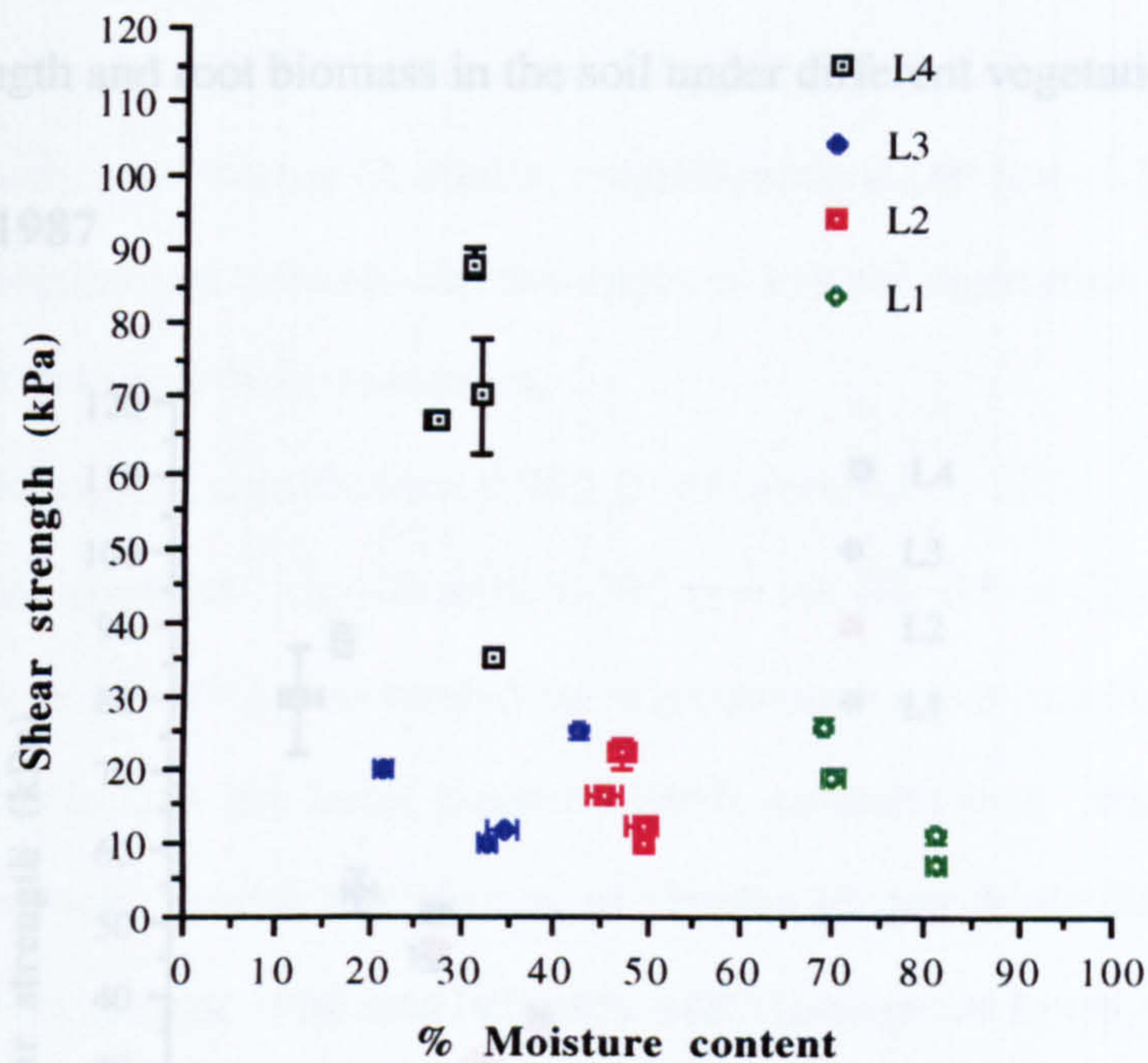


Fig. 4.9: Shear strength Vs. Moisture content variations (February 1987)
P. arundinacea cultivated banks

Figs. 4.9 and 3.8a, present similar patterns of shear strength and moisture content variations between the bare plots and those sown with *P. arundinacea* seeds in August 1986. The variation of shear strength in the *P. arundinacea* sown banks indicates a steep increase in the values in the uppermost region of the bank (Level 4). This may be attributed to the seedling establishment on the apical plateau region of the banks at Level 4. There was erosion of patches of top soil with *P. arundinacea* seedlings at levels 1,2 and 3, from October 1986 to January 1987 due to the fluctuating hydrograph of the river, there was no such loss of soil or plants at level 4.

While the above comments are in keeping with the observations on both seedling establishment and shear strength values, it is inappropriate to arrive at hasty conclusions based on limited samples. As mentioned previously, the study of shear strength and moisture content variations is treated in this thesis as a subsidiary aspect to variations of erosion under different types of vegetation and bare soil. The above comments on the effects of *P. arundinacea* establishment on shear strength of the soil need confirmation on

the basis of a major research study. It has to be stressed that other authors (cf Scholand et al, 1991) who analysed data based on limited samples found no correlation between shear strength and root biomass in the soil under different vegetation.

b) *P. arundinacea* versus *U. dioica* : significance 0.140 ($t = -1.533$);

August 1987

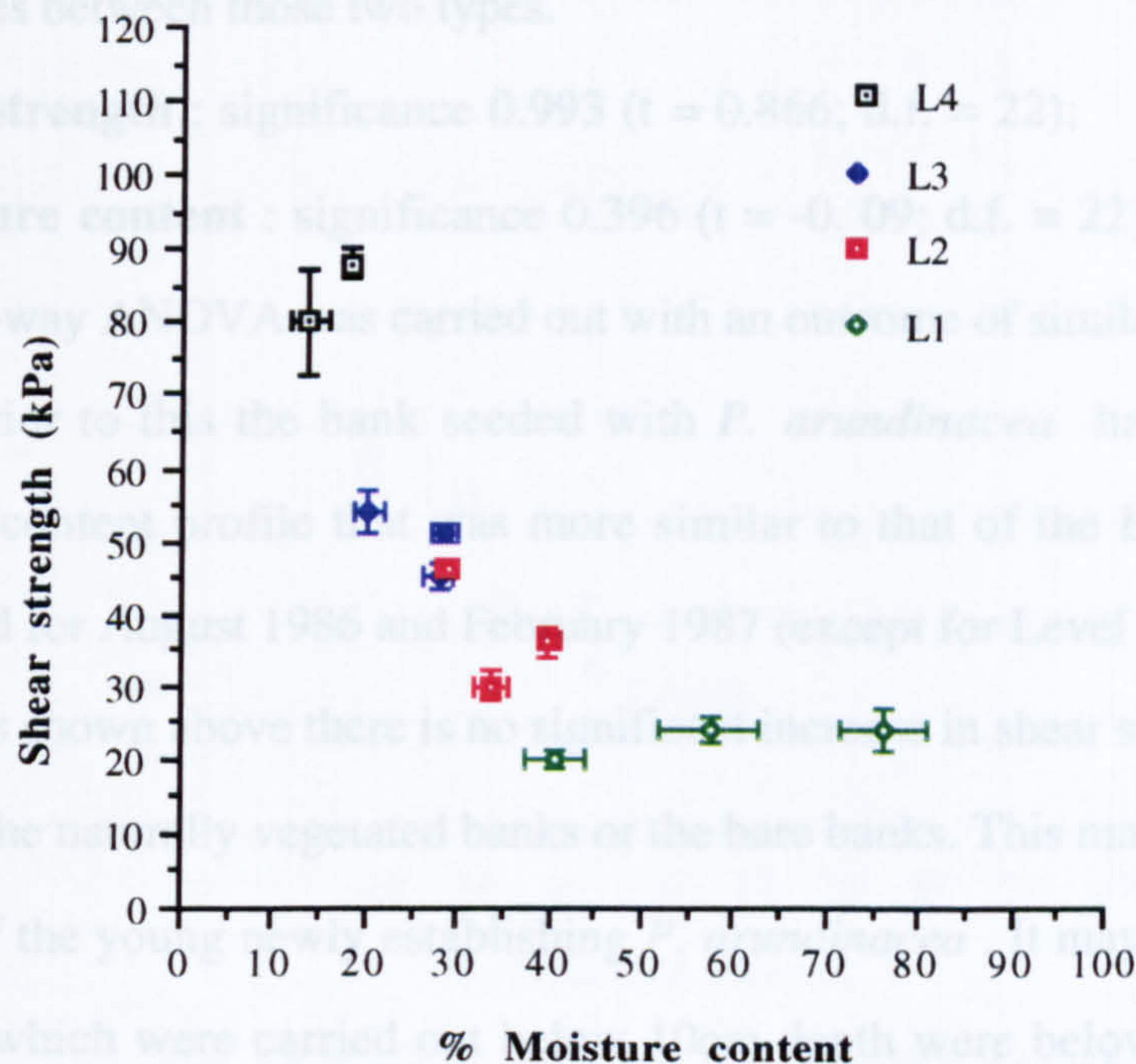


Fig. 4.10: Shear strength Vs. Moisture content variations (August 1987) *P. arundinacea* cultivated banks

There is an increasing similarity between the values of shear strength and moisture contents on the profiles of the *P. arundinacea* vegetated banks with those of the naturally vegetated banks. t- tests for the performance of *P. arundinacea* in comparison with the two types of natural vegetation indicated the following results on analysis based on whole banks (mean values of all 4 levels together) :

i. shear strength Both types of natural vegetation (i.e. one dominated by *E. hirsutum* and the other by *U. dioica*) showed no significant differences at 95% confidence level.

a) *P. arundinacea* versus *E. hirsutum* : significance of 0.652 ($t = 0.458$; d.f. = 21);

b) *P. arundinacea* versus *U. dioica* showed a significance value of 0.660 ($t = 0.446$; d.f. 21).

ii. moisture content

Both types of natural vegetation showed no significant differences.

a) *P. arundinacea* versus *E. hirsutum* : significance 0.422 ($t = -0.818$; d.f. = 2);

b) *P. arundinacea* versus *U. dioica* : significance 0.140 ($t = -1.535$);

A similar test between the two types of natural vegetation indicated no significant differences between those two types.

i. shear strength : significance 0.993 ($t = 0.866$; d.f. = 22);

ii. moisture content : significance 0.396 ($t = -0.09$; d.f. = 22);

(N.B. a 2-way ANOVA was carried out with an outcome of similar significance values)

Prior to this the bank seeded with *P. arundinacea* had a shear strength and moisture content profile that was more similar to that of the Bare bank treatment, as mentioned for August 1986 and February 1987 (except for Level 4 by February 1987).

As shown above there is no significant increase in shear strength values from that of either the naturally vegetated banks or the bare banks. This may be due to the low root density of the young newly establishing *P. arundinacea*. It may be that the shear vane readings which were carried out below 10cm depth were below the root levels of the newly established vegetation.

It would be pertinent to consider the effects of variations of tensile strengths of young and mature roots in terms of shear strength values imparted on to the soil. This may have a significant effects on shearing resistance offered to the shearing device. Waldron (1977) and Gray (1974, 1978, 1982) demonstrate the importance in accounting for the tensile strength of the roots in discussions on the increase of shear strengths imparted by different root system. While this study did not include the measurement of tensile strengths of roots, there may be a differential effect between a young and a mature root. Young roots may not have sufficient lignification as mature roots thereby offering lesser shearing resistance.

The fact of significance is that the young *P. arundinacea* roots (or the shoots) reduced erosion (see Fig. 4.2) even though they did not increase the shear strength of the soil as measurable by the shear vane at this stage of growth. Therefore, the alternative

proposal has to be that it was the presence of shoots and not the roots (via a dense root mattress or shear strength) that reduced bank erosion.

February 1988

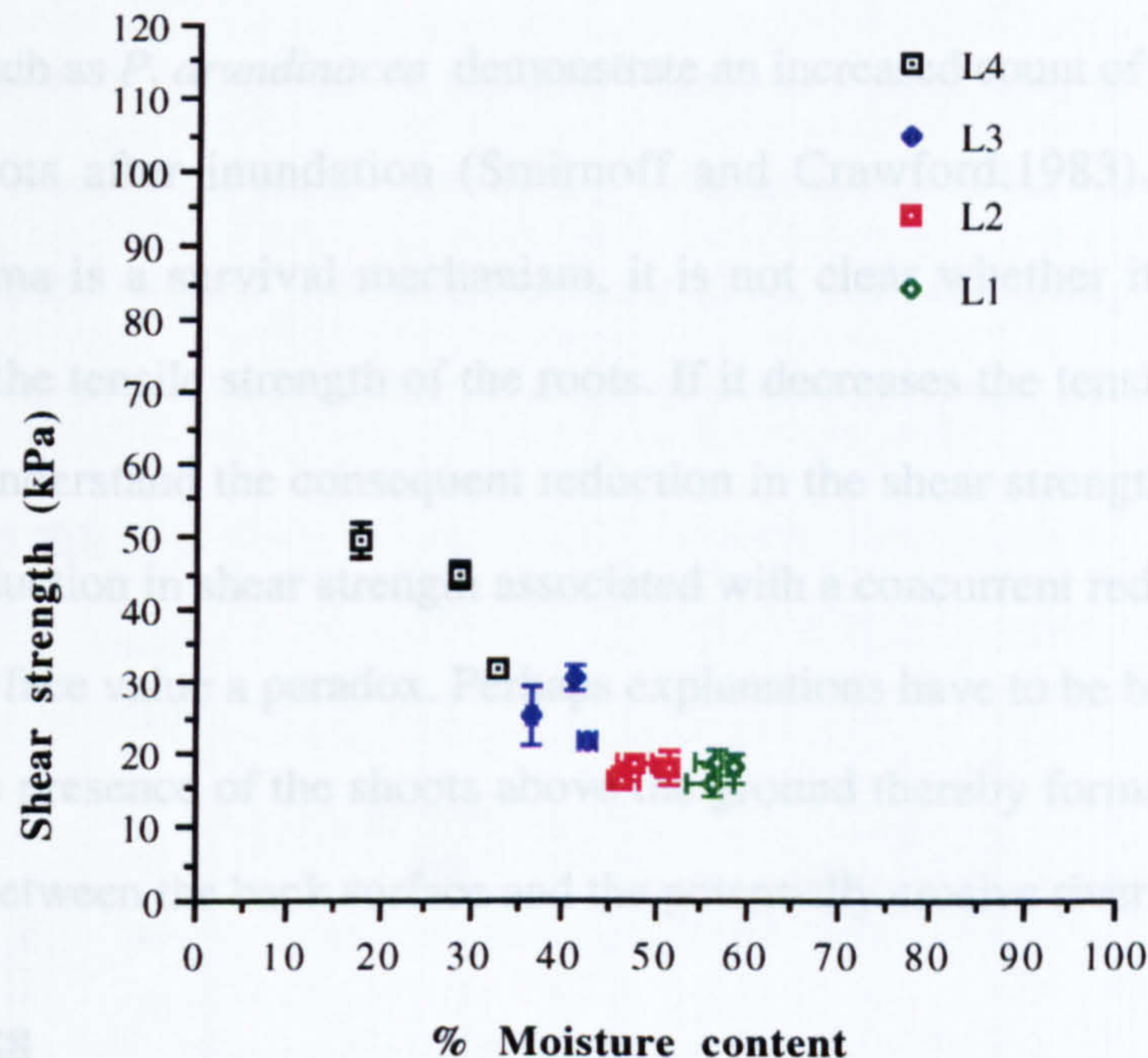


Fig. 4.11: Shear strength Vs. Moisture content variations (February 1988) *P. arundinacea* cultivated banks

As mentioned in 4.4.2b the long flood of October to January 1987 played its role in erosion of some of the newly establishing plants of *P. arundinacea*. As shown in Fig.4.2 erosion continues in the banks under the newly emergent *P. arundinacea*. to a level similar to that of the naturally vegetated banks.

Consequent to the long flood incidence there is a marked reduction in the shear strength values of all the representative plots of the treatments in this study. It is not explainable in terms of percentage moisture content prevalent at the time of measurements as they themselves are low (see Figs. 4.11, 3.10a, 3.10b and 3.10c). The discussion and explanations cannot be limited to the percentage moisture content in a simplistic manner. Rosenak (1963) discusses the relevance of pore water pressure on cohesion and hence the shear strength of the soil. Thorne (1978) discusses pore water pressure in relation to river banks and the quantification of shear strength both in situ (by a shear vane) and under laboratory conditions (triaxial test). In addition, the theoretical arguments on other

aspects such as plasticity, all require a major research effort to understand how a river bank which has low /similar shear strengths under different types of vegetation and bare soil has much reduced erosion for the vegetated areas while the bare areas erode quite considerably.

The above aspects are even more complicated by the fact that flood-tolerant species such as *P. arundinacea* demonstrate an increased count of aerenchyma production in the roots after inundation (Smirnoff and Crawford, 1983). While production of aerenchyma is a survival mechanism, it is not clear whether it will increase or even decrease the tensile strength of the roots. If it decreases the tensile strength of the roots one can understand the consequent reduction in the shear strength of the soil. However, such a reduction in shear strength associated with a concurrent reduction in erosion of the bank is at face value a paradox. Perhaps explanations have to be based not on root effects but on the presence of the shoots above the ground thereby forming an effective cover (barrier) between the bank surface and the potentially erosive river flow.

May 1988

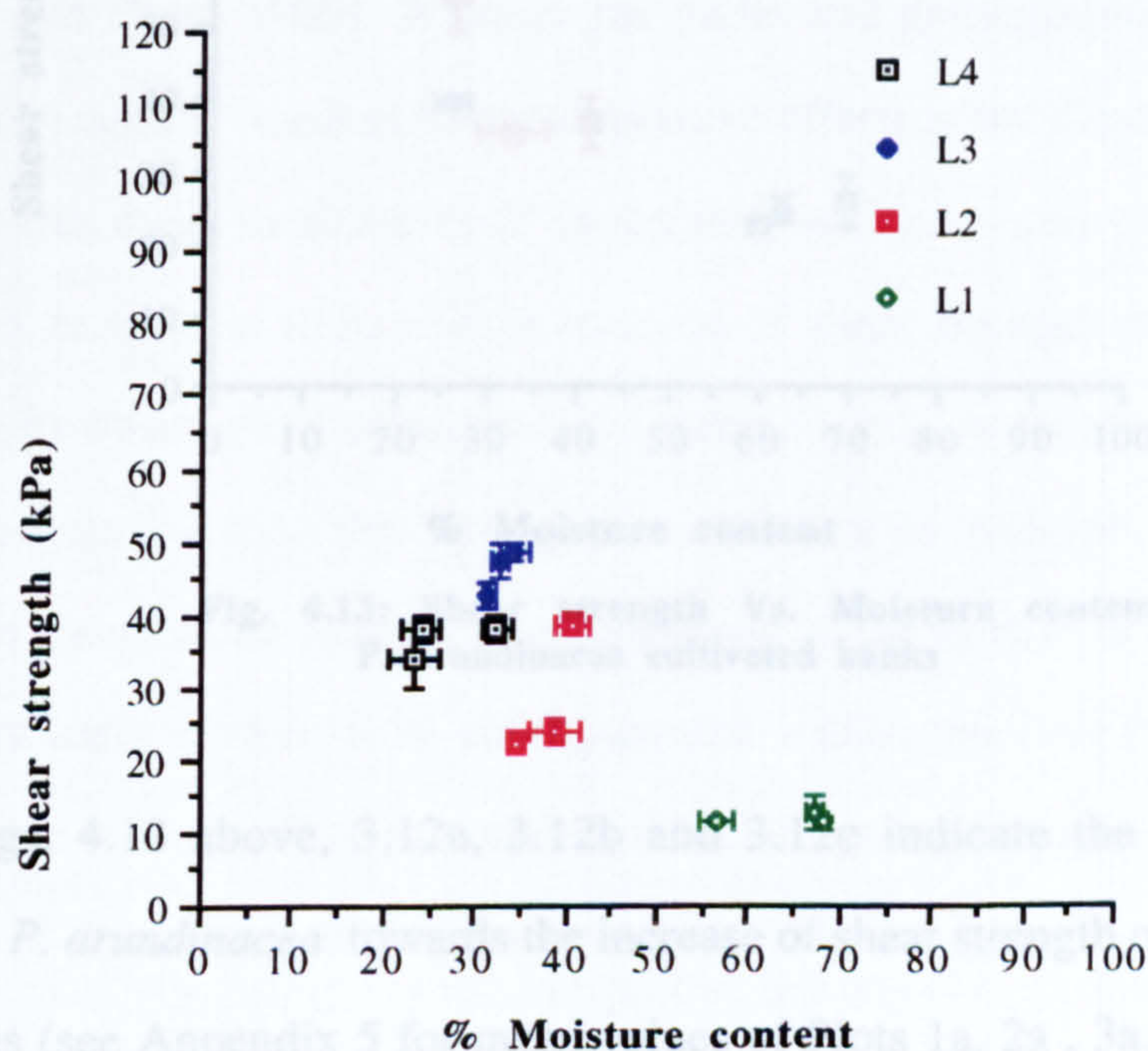


Fig. 4.12: Shear strength Vs. Moisture content variations (May 1988)
***P. arundinacea* cultivated banks**

Figs. 4.12 above, 3.11a, 3.11b, and 3.11c show hardly any difference in shear strength and moisture content profiles worthy of comparative analysis. The low shear strength

values in both the naturally vegetated and the *P. arundinacea* plots may be due to the death and decay of roots in the former (Hendry and Brocklebank, 1985) or the production of aerenchymatous tissue in the latter (Smirnoff and Crawford, 1983) as a consequence of the prolonged flood of October 1987 to January 1988. Etherington (1983) concludes that in *E. hirsutum* shallow adventitious roots are formed at the expense of the deep primary roots as a response to flooding. There is a possibility that the new roots were above the level of the shear vane during measurements of the shear strength. However as mentioned for August 1987 and February 1988, the probability is that the reduction of erosion is more attributed to the presence of shoots as a bank cover.

August 1988

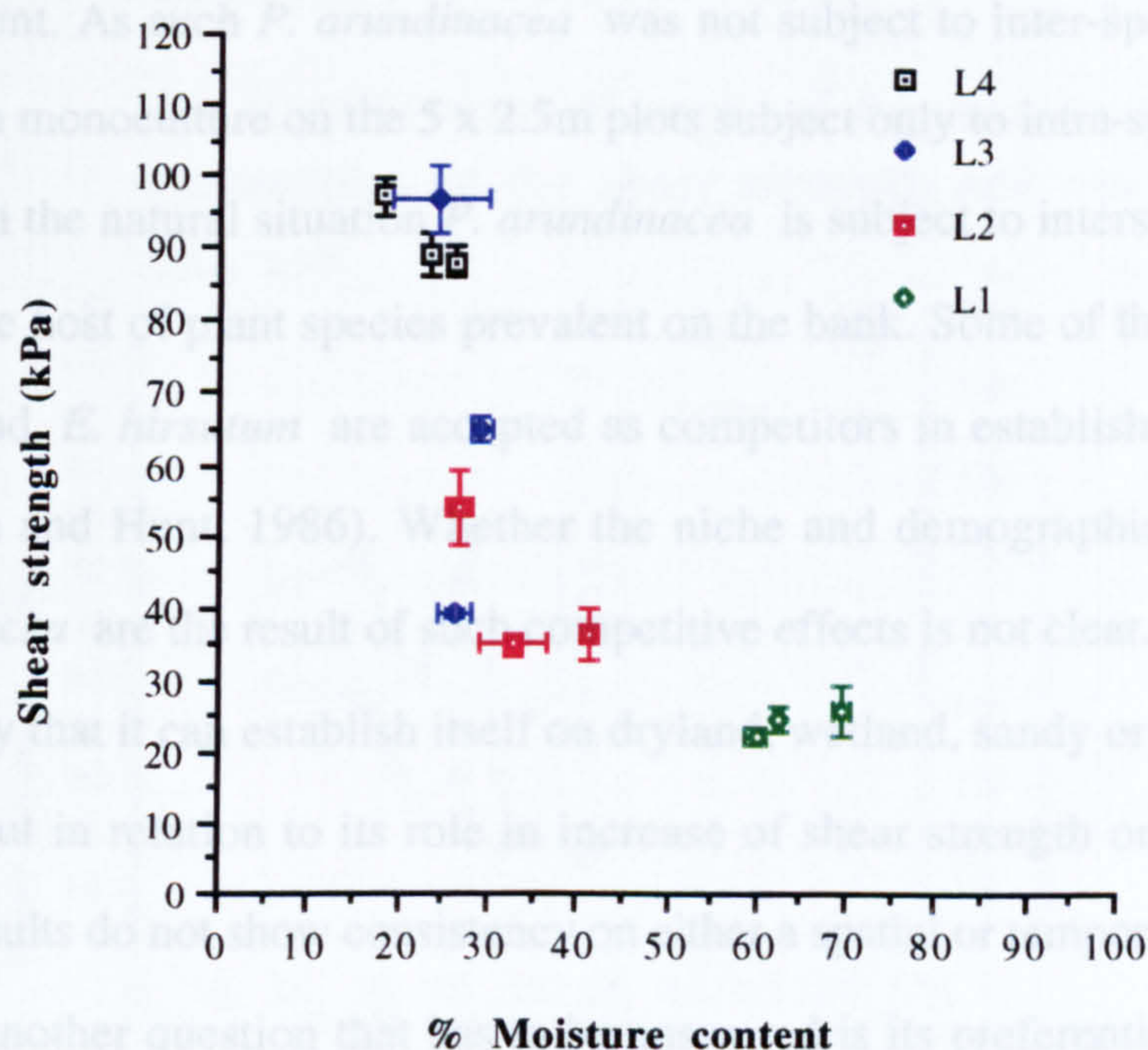


Fig. 4.13: Shear strength Vs. Moisture content variations (August 1988)
P. arundinacea cultivated banks

Figs. 4.13 above, 3.12a, 3.12b and 3.12c indicate the positive contribution played by *P. arundinacea* towards the increase of shear strength of the soil of the banks. The values (see Appendix 5 for mean values of Plots 1a, 2a, 3a, 5a for levels 1, 2, 3, and 4) are the highest compared with both natural vegetation and the bare plot. Perhaps with time the pattern and density of establishment of this grass on the bank may change. The pattern existent by August 1988 was one of tall, robust dense distribution of plants at levels 2 and 3 with a short, but very dense matting of plants in level 4. At Level 1 (toe-

region) there was fast proliferation of *P. arundinacea* from Level 3 downwards to the waterline (see Plate 7). This was similar to the long-term established clumps of this species prevalent in other parts of the bank of this river and the larger River Ouse flowing through Buckinghamshire and Northamptonshire. The difference was that while the cultivated plots were a monoculture from the base to the top of the bank the naturally colonised clumps in other parts of the river were limited to Levels 1 and 2 mostly.

As an artificially cultivated bank vegetation one significant factor was missing from this when compared with colonies of *P. arundinacea* that share a bank. That is the ecologically significant aspect of inter-specific competition. In the cultivated monoculture all naturally establishing plants were carefully weeded out by hand throughout the experiment. As such *P. arundinacea* was not subject to inter-specific competition and grew as a monoculture on the 5 x 2.5m plots subject only to intra-specific competition.

In the natural situation *P. arundinacea* is subject to interspecific competition by the whole host of plant species prevalent on the bank. Some of these species such as *U. dioica* and *E. hirsutum* are accepted as competitors in establishment strategy (Grime, Hodgson and Hunt, 1986). Whether the niche and demographic characteristics of *P. arundinacea* are the result of such competitive effects is not clear. *P. arundinacea* has a versatility that it can establish itself on dryland, wetland, sandy or silty soil (Grime et al, 1986). But in relation to its role in increase of shear strength on the bank profile, the above results do not show consistency on either a spatial or temporal basis.

Another question that has to be answered is its preferential habitat on the bank profile. On the artificial monoculture cultivation on the bank *P. arundinacea* was limited to the mid bank region in its establishment within the first two seasons. This was probably due to its inability to establish as seedlings on the toe-region, however much it is capable of dominating this region in the latter stages.

It was only at the last stages of experimentation (Phase 5) that *P. arundinacea* colonised the toe-region (waterline) as shown in Plate 8. By this stage certain aspects of ecological significance were evident. They were (a) the toe-region was open to colonisation by any species; (b) the closest growing species was *P. arundinacea*; (c) the

mid to upper bank region was densely colonised by already established *P. arundinacea* plants. However, in the natural situation it may obviously be competed out by other competitors such as *U. dioica* from the upper and mid bank region. The result is that rather than being competed out from the given area of land (in this case the bank) it is forced into the waterline as a habitat, where it can survive without competition from species such as *U. dioica* . This mode of argument is strengthened by the fact that *U. dioica* or *E. hirsutum* do not prefer the waterline as observed along the rivers. They prefer the mid-regions of the bank which are less subjected to trampling by man, leaving the upper banks for the grasses which tolerate trampling by man. It is therefore questionable whether the toe-region is the 'preferred' or the 'realised' niche of *P. arundinacea* in the process of secondary succession.

4.5.2. The establishment of roots of *P. arundinacea* and its possible relationships to the shear strength and moisture content of the bank soil

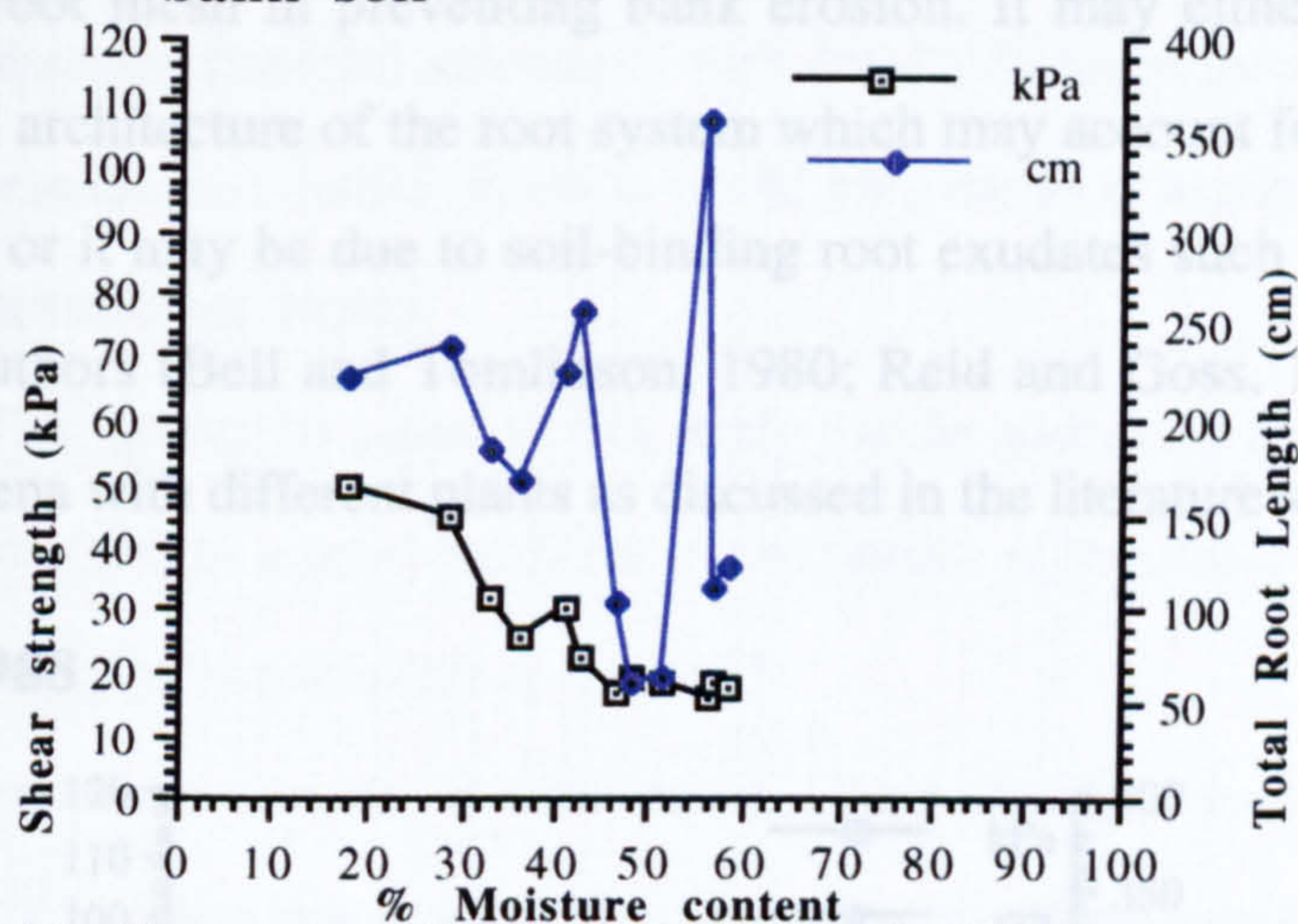


Fig.4.14: Shear strength, Root length and Moisture content variation (February 1988) *P. arundinacea* cultivated banks

The main observation is that by February 1988 *P. arundinacea* had established its root system much more (Fig 4.14) than either type of natural vegetation (Figs 3.13a - c). This means that the root establishment at the top soil, to a depth of at least 20cm, throughout the bank had been so much that it surpasses the density of roots of long established normal bank vegetation which may have a dominant *U. dioica* or *E. hirsutum* or other normal bank grass species. The root density in terms of length per unit volume of soil varies between 50 to 350cm /cm³ (see data in Appendix 5). The shear strengths vary

in the range of 10 to 50 kPa which is not significantly higher (at 95% confidence levels) in comparison with normal vegetation. The reason for this may be the development of more aerenchymatous tissue (Smirnoff and Crawford, 1983) consequent to the prolonged flood of 1987/88. It has to be pointed out that the *P. arundinacea* plots showed a significant reduction in the rate of erosion of the whole banks between August 1987 and February 1988 (see Fig. 4.2). This is interesting as the same reduction in erosion was the direct result of one season's growth of this grass. If this reduction of erosion is not due to any considerable increase in shear strength of the soil, then it may be due to some other phenomenon associated with the grass. Where the high density of the foliage is considered it may be proposed as a valid reason for negating erosion. Even in February with its wintry limitations on the foliage for most bank vegetation such as *E. hirsutum* and *U. dioica*, *P. arundinacea* retains a dense (litter) foliage (Grime et al, 1986).

The higher root density than *E. hirsutum* and *U. dioica*, indicates a possible role of this root mesh in preventing bank erosion. It may either be a direct result of the physical architecture of the root system which may account for an adaptive architectural strategy or it may be due to soil-binding root exudates such as muco-polysaccharides. Other authors (Bell and Tomlinson, 1980; Reid and Goss, 1980) have observed these phenomena with different plants as discussed in the literature survey.

May 1988

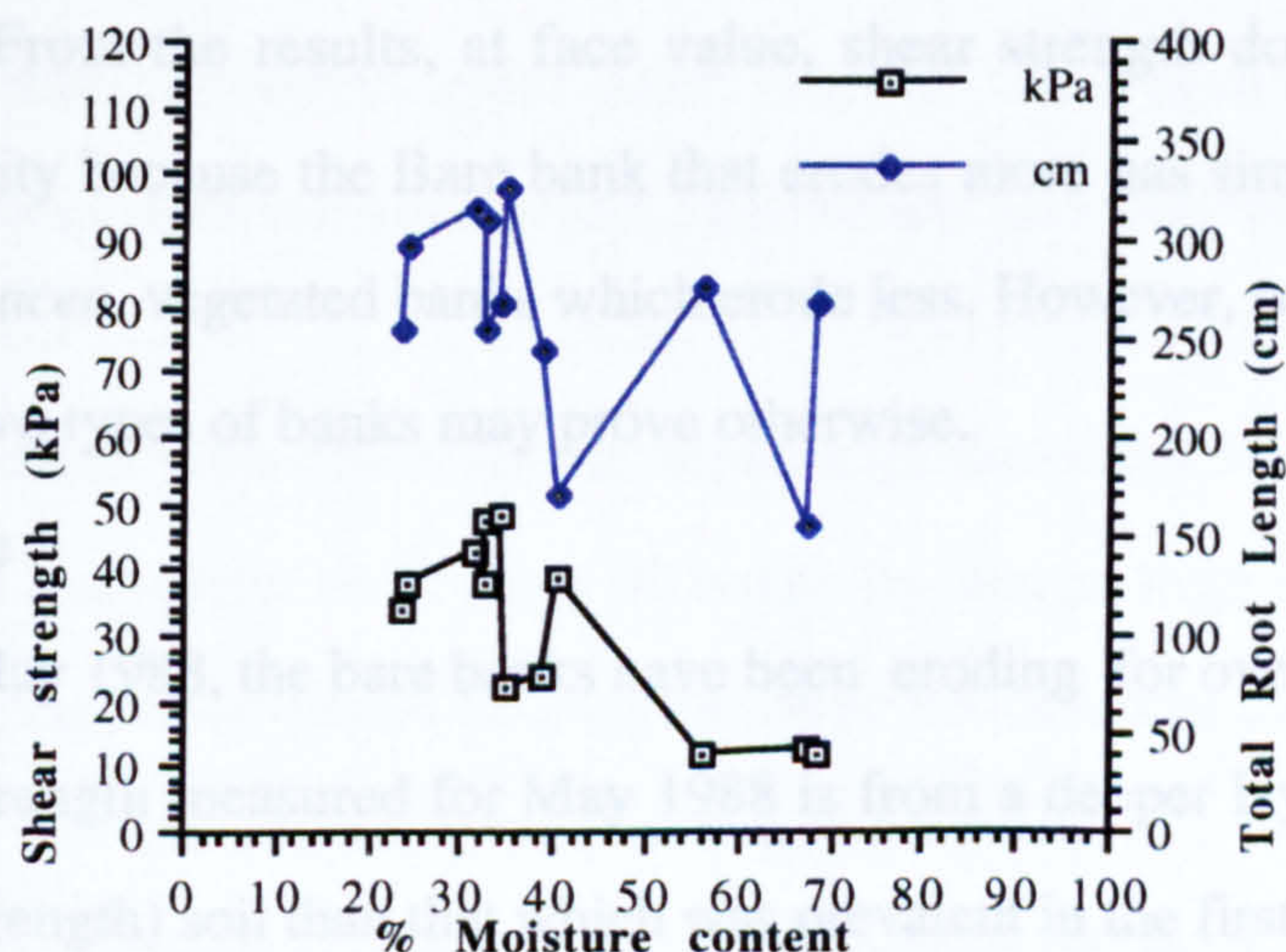


Fig. 4.15: Shear strength, Root length and Moisture content variation (May 1988)
P. arundinacea cultivated banks

By May 1988 there is hardly any increase in the root density or the shear strength for the *P. arundinacia* plots when compared with the data for February. The explanation for this temporary cessation in the increase of roots per unit volume of soil may be attributed to seasonal variation in the growth characteristics of shoots and roots of a plant. By spring the plants divert their stored energy to produce more shoots. The result is a temporary period of constant root density. It may not be a temporary cessation of root production but the plant may control the dynamics of root production in such a fashion as to allow compensation for dying roots only.

Conclusion

The comparison of the Bare versus *P. arundinacea* plots with regard to shear strength and total root length present in the soil during May 1988 indicates (cf Fig. 4.15 and 3.14a) that roots do not contribute to shear strength of the soil. The bare bank has a very similar shear strength throughout its profile to that of the *P. arundinacea* vegetated bank. However, the total amount of root density is nil in the bare banks but very high in the *P. arundinacea* banks. Erosion in the bare banks is higher (see Fig. 4.1) than that of the *P. arundinacea* banks.

Two questions central to this study maybe addressed from these results. They are :

- i) is shear strength a good predictor of erodibility of the soil ?
- ii) do roots affect erodibility of the soil?

From the results, at face value, shear strength does not act as a predictor of erodibility because the Bare bank that erodes more has similar shear strengths to the *P. arundinacea* vegetated banks which erode less. However, two aspects which are intrinsic to the two types of banks may prove otherwise.

They are :

- a) By May 1988, the bare banks have been eroding for over two years. It means that the shear strength measured for May 1988 is from a deeper layer of more compact (higher shear strength) soil than that which was prevalent in the first six months of the study. For *P. arundinacea* vegetated banks the soil level at which shear strength was measured remained higher than that for the concurrent reading of the Bare bank. This was because of less erosion over the two years.

b) the Bare banks were exposed to weathering and did undergo minimal erosion due to dry winds; this did not happen for the *P. arundinacea* banks as they were covered with the foliage thereby preventing surficial erosion. As such weathering of exposed banks is associated with higher erosion.

August 1988

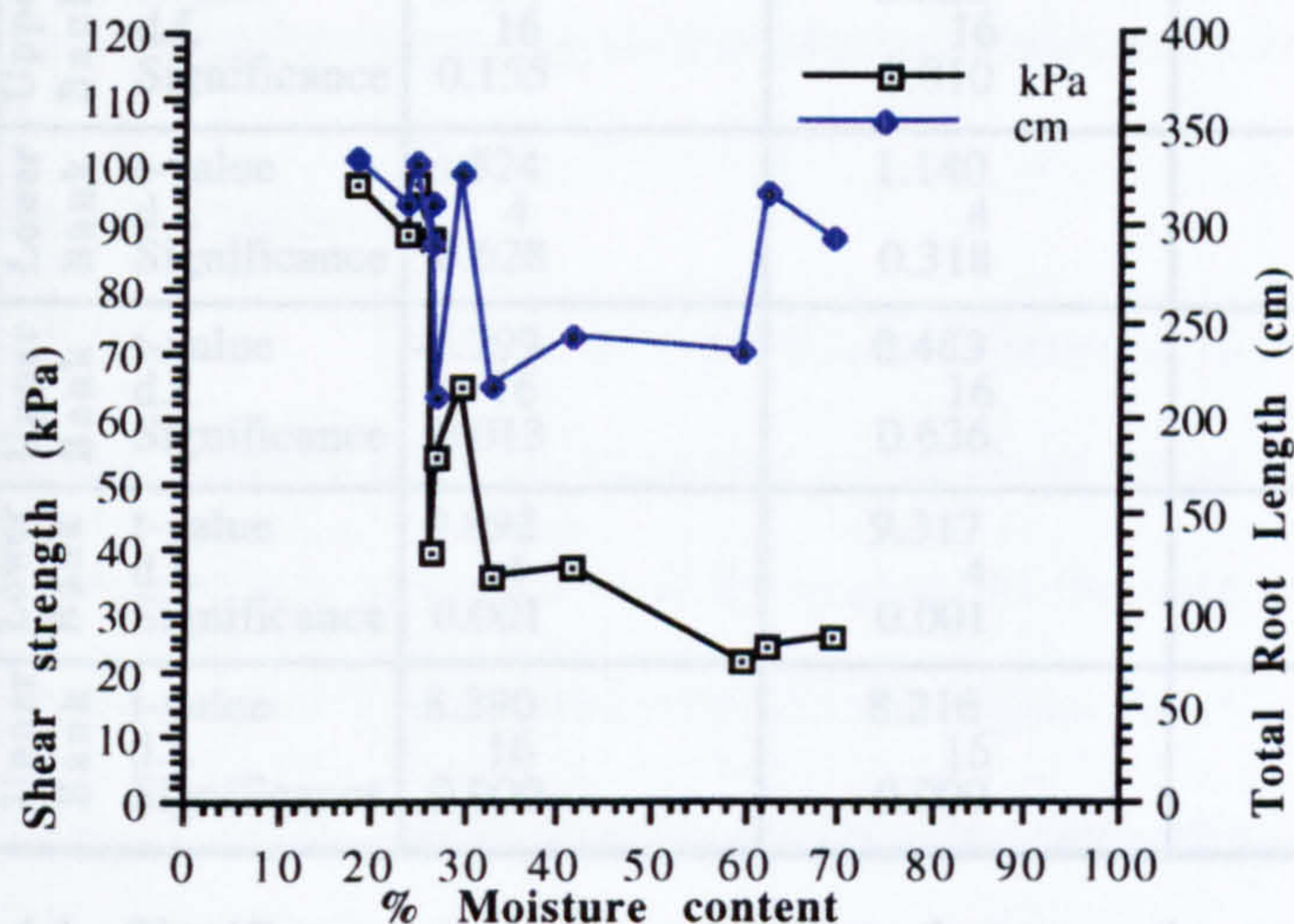


Fig. 4.16: Shear strength, Root length and Moisture content variations (August 1988) *P. arundinacea* cultivated banks

It is best to compare the data for the three vegetated bank types (*P. arundinacea* cultivated, natural vegetation dominated by *E. hirsutum* and natural vegetation dominated by *U. dioica*) used in these experiments as measured for August 1988. The main reasons are :

- i. all three vegetation types have reached full vegetative growth by August; *P. arundinacea* cultivated plots have matured and are flowering by August 1988 (see Plates 2 and 7);
- ii. they are in 'preparation' for the winter high flows that would inevitably arrive shortly;
- iii. in a discussion on erosion of banks by winter high flows, as prevalent in Great Britain, this period should be a critical stage for factors of root structural implications (eg. density, root-soil cohesion and root tensile properties). In the three parameters quantified (i.e. shear strength, moisture content and root length per unit volume of soil) ideally all three root structural implications should be reflected.

			<i>P. arundinacea</i> vs. Natural vegetation dominated by <i>E. hirsutum</i>	<i>P. arundinacea</i> vs. Natural vegetation dominated by <i>U. dioica</i>	Natural vegetation dominated by <i>E. hirsutum</i> vs. Natural vegetation dominated by <i>U. dioica</i>
Shear strength (kPa)	Lower Bank	t-value d.f. Significance	7.309 4 0.002	9.306 4 0.001	1.003 4 0.372
	Upper Bank	t-value d.f. Significance	1.494 16 0.155	2.922 16 0.010	1.177 16 0.257
Moisture content (%)	Lower Bank	t-value d.f. Significance	0.524 4 0.628	1.140 4 0.318	0.853 4 0.442
	Upper Bank	t-value d.f. Significance	-2.799 16 0.013	0.483 16 0.636	3.465 16 0.003
Root length (cm)	Lower Bank	t-value d.f. Significance	9.898 4 0.001	9.317 4 0.001	-0.259 4 0.808
	Upper Bank	t-value d.f. Significance	8.390 16 0.000	8.216 16 0.000	-0.153 16 0.880

Table 4.1. Significance tests for variations between the main parameters for the three vegetation types (August 1988); (t-tests) for comparisons of Shear strength, Moisture content, and Root density between two types of naturally vegetated banks and *P. arundinacea* cultivated banks;

(see Appendix 6 for mean data of the above analysis)

N.B. The data can be analysed on a 3-way Anova, but the author preferred the permutational analysis as shown above.

Table 4.1summarises a series of t-tests used in comparisons of the means of the three parameters measured. The presentation in the table is permutational (i.e. three factors of A,B,C, can be compared as AB, AC and BC). This presents a series of significance values for within the lower bank (Level 1) and within the upper bank (Levels 2,3 and 4).

The significance values and their interpretations can be summarised as :

i. Shear strength

a) Lower banks There is a significantly higher shear strength for *P. arundinacea* when compared with naturally vegetated banks dominated by *E. hirsutum* as well as *P. arundinacea* and naturally vegetated banks dominated by *U. dioica*. This is because there

are more roots in this region of the *P. arundinacea* cultivated banks. But there is no such significant difference between the natural vegetation types.

b) Upper banks *P. arundinacea* has a significantly higher shear strength than naturally vegetated banks dominated by *U. dioica*. while no such significance is evident for *P. arundinacea* and naturally vegetated banks dominated by *E. hirsutum* . Probably the grasses at Level 4 in the *U. dioica*. plots influenced the mean shear strength values of this treatment thereby imparting similar characteristics to *P. arundinacea* .

ii. Moisture Content

a) Lower banks There is no significant difference between any of the treatments. This is in accordance with the expected as all three vegetation types covered the bank surfaces very densely at this time of the season. In the case of *E. hirsutum* and *U. dioica* the shoots from level 3 were bent over the toe-region. In *P. arundinacea* plots there was colonisation by young plants thereby shading the bank. In addition the flow levels in the river were ambient.

b) Upper banks There is a significant difference between the *P. arundinacea* and naturally vegetated banks dominated by *E. hirsutum* but not between *P. arundinacea* and naturally vegetated banks dominated by *U. dioica* there is no explanation the author can offer for this.

iii. Total root length per unit volume of soil

a) Lower banks As expected *P. arundinacea* vegetated bank have a much higher root density than naturally vegetated banks dominated by *E. hirsutum* and naturally vegetated banks dominated by *U. dioica*.. There is no significant difference between the two naturally vegetated types.

b) Upper banks the same comments as for the lower banks apply to the upper banks in relation to root density.

This confirms that *P. arundinacea* offers both higher shear strength and root density on to the lower and upper banks of a river. In terms of bank protection, this is an ideal species for wetland bank consolidation. The fundamental practical advantage is that it establishes in the drier upper banks and invades into the wetter lower banks thereby

consolidating the lower banks. On an actively eroding bank (as in the experiment) *P. arundinacea* established on the banks within one season as a highly satisfactory vegetation type to negate erosion and stabilise banks. Perhaps layering of rhizomes may be a more effective measure for quicker results in preventing bank erosion in actively eroding banks with fluctuating flow levels.

This latter part of summer is characterised by plants switching priorities of energy diversion for biomass production more towards root production rather than shoot production. The explanation for such a change of priorities may be that the plant needs to establish more roots before the winter because the probability of it being uprooted by winter floods (an inherent adaptive attribute) is higher if it had a poor root system with large dead foliage attached to it. Large dead or dying foliage would increase the drag with the motive force of the water. Hubbard (1984) and Marten (1985) report that *P. arundinacea* in fact develops a deep and extensive root and rhizome system as it matures.

4.6. Main Conclusions

In this research proposal, of all the vegetation types *P. arundinacea* was expected to show the best results in confirmation of the first hypotheses (roots increase shear strength of the soil and therefore decrease its erodibility). This was based on the fact that unlike the other species in this study (*U. dioica* and *E. hirsutum*), *P. arundinacea* has a fibrous root system. It is also well known for its efficient root establishment and the formation of rhizomes. However, the results obtained do not confirm the hypothesis. For example, in February 1988 when the banks were established with *P. arundinacea* there was no correlation of root density with increases in bank shear strength in the lower banks. While some correlation is apparent in the upper bank (Fig. 4.14) it does not prove an increase in shear strength when compared with the Bare Banks (Fig. 3.13a). By May 1988 there is a similar pattern of correlation but no significant increase in shear strength when compared with the Bare banks. In August 1988 even though shear strength reaches 100kPa (Fig. 4.16) it does not explain a root effect because the Bare banks (Fig. 3.15a) show a high shear strength (15-20kPa) in the absence of roots. As such even though mean erosion rates are significantly lowered for *P. arundinacea* hypothesis one is not feasible.

On the contrary, results, analysis and the relevant discussions on comparisons within the upper versus lower banks (4.4.2c) as well as those between treatments (4.4.2a, 4.4.2b, 4.4.2d, 4.4.2e, 4.4.2f and 4.4.2g) show that the shoot system of *P. arundinacea* has reduced the erodibility of the bank in keeping with the rate of its above ground establishment. Therefore, it is concluded that hypothesis two (phyllospheric effects influence bank erodibility through its physical presence as a bank intermediary) holds true.

The presence of a reasonable distribution of live roots in the winter as reflected in the February 1988 measurements (Fig. 4.14) poses the question as to what specific role the roots play in terms of bank protection. However, until further research (see Ch. 7) confirms whether they serve as anchorage for the winter foliage or serve as bank protectors through other functions, a conclusion cannot be arrived at on the specific function/s of the roots in negating erosion of banks in winter. It is reasonable to assume that these live roots did encompass anchorage as it is a primary function of a plant root. Therefore, in the knowledge that through the phyllosphere retained during winter, *P. arundinacea* reduced the erosion of its habitat it is reasonable to state that without the roots as anchorage the shoot system may have washed down the river.

Other conclusions

- i) initial establishment of *P. arundinacea* on the banks of a waterway is subject to the seasonal and the hydrographic variations. The technique of hand broadcasting of seeds for germination and establishment of a uniform growth of plants is not to be recommended on channel banks with frequently fluctuating hydrographs. However, in one season the established plants reproduce vegetatively and colonise the bare banks quite efficiently;
- ii) on a comparative basis, *P. arundinacea* having established in a short period of time on actively eroding banks, not only consolidated the banks but reduced erosion to levels closely similar to those of normal bank vegetation;
- iii) under the broadcast seeding method the initial colonisation is higher in the upper regions of the bank than the bank toe region;

- iv) upper bank erosion is almost totally arrested by this species in the establishment within one season;
- v) the lower region of the bank shows a significant reduction in erodibility only at the end of the second season of growth. This may be a reflection of late colonisation by established plants from above (see Plate 8), together with an initial inability for this species to germinate from seeds at the fluctuating flow levels at the toe region;
- vi) *P. arundinacea* does not show much immunity from possible low root turnover or death during long-term floods as root length data indicate for early 1988;
- vii) the early summer months indicate a relatively lower root production than shoot production. The phenomenon has been discussed in more detail with possible explanations;
- viii) in late summer increases in root density are observed; The possible implications and the relevant operative phenomena have been discussed.

Chapter 5

Experiment 3 :An investigation of the process of natural re-vegetation of a river bank, consequent to denudation by a systemic herbicide

5.1. Introduction

Different authors have discussed the importance of bank vegetation in preventing erosion or affecting the mode of erosion and mass failure under vegetated overhang (eg. Thorne and Tovey, 1981). However there is clearly a vacuum in theory, experimentation and predictions on the process of natural succession on bare, devegetated or eroded banks. River systems as dynamic entities change their courses with time. Hence we find the braided and compounded river systems. Bank erosion which initiates this process encompasses the process of exposing new bare banks and formation of channel bars which are naturally vegetated with time. Establishment of vegetation within the river corridor is discussed by Hooke (1986) within the process of plant colonisation patterns of mid-channel bars in actively meandering rivers.

From that study (Hooke, 1986) there is reason to believe that a physical process of geomorphic significance to the river corridor and an ecological process of vegetation succession act in an inter-dependent manner. They are:

- (a) development of the mid-channel bar (with the first stages of deposition of a layer of coarse material followed by the later stages of accretion of height and the final attachment of the former mid-channel bar to the floodplain); and
- (b) vegetation establishment and succession (with the first stages of sparse vegetation of low herbs such as *Trifolium pratense*, *Ranunculus acris*, *Rumex obtusifolius* to taller species such as *Epilobium hirsutum* followed by *Impatiens gladiifera* and finally the trees such as *Salix* spp.). While the initiation of the mid-channel bar is not dependent on establishment of vegetation, the subsequent stages of (a) and (b) are inter-dependent.

In addition, the process of colonisation described is similar to that of secondary succession observed for land plants where herbs, shrubs and tree species colonise in succession on a long-term time scale. The significance of such colonisation is that it leads



Plate 9. **De-vegetated bank assigned for natural re-vegetation (September 1986)**
 N.B. thick layer of dead vegetation left intact

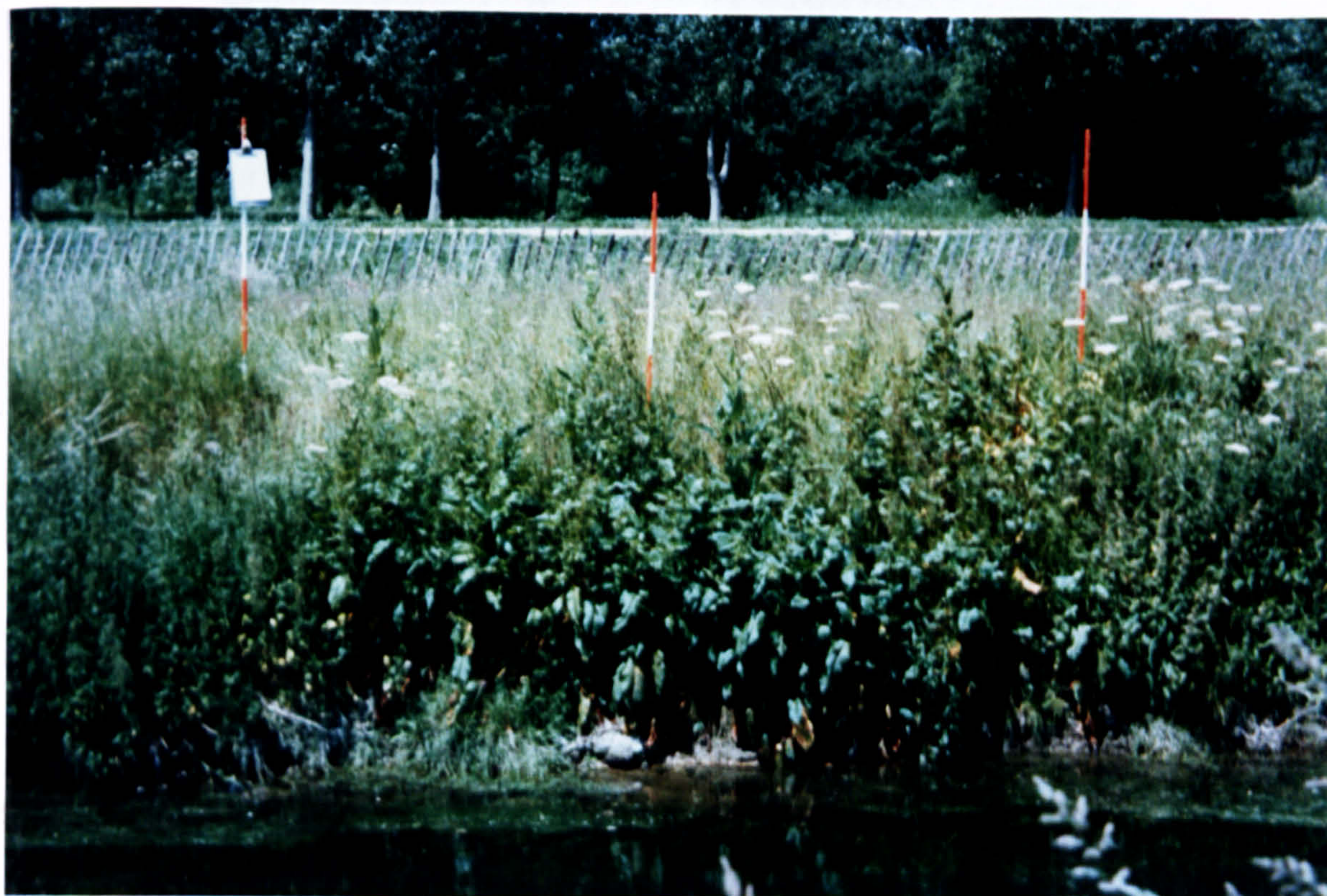


Plate 10. **De-vegetated bank assigned for natural re-vegetation (June 1988)**
 N.B. colonisation by grasses and *Rumex* spp.



Plate 11. Upper bank (levels 3 to 4) of a naturally re-vegetated bank with poor colonisation
 N.B. photographed along the bank (laterally); strip of dry, hollow bank almost devoid of vegetation



Plate 12. Lower and mid-bank colonisation in a naturally re-vegetated plot (August 1988)
 N.B. *Rumex* spp. and grasses dominate this region as a pioneer coloniser in secondary succession

to an on-going process of deposition and accretion of soil with the aid of the establishment of vegetation spatially and temporally. It must be stressed that both processes involve deposition rather than erosion. The question is whether such natural colonisation and succession of vegetation did have any effect on negating erosion of the mid-channel bars at storm flow periods of the river.

This study addresses the above question for the river banks rather than for mid-channel bars. It studies erosion on a similar bare exposed bank which is naturally re-vegetating. The aspects are quantified on a temporal and spatial basis.

Plant succession constitutes a series of stages in reaching a climax natural vegetation. Clements (1916) who was a pioneer of studies on succession depicted the stages as : 1. Nudation, 2. Migration, 3. Ecesis 4. Competition, 5. Reaction, and 6. Final stabilization. The banks of this experimental area had been colonised by plants over the last 20 years. It has a bank vegetation community similar to that observed by others for lowland British rivers (Holmes et al, 1973; Holmes and Whitton, 1975 and Haslam, 1978).

This experiment of natural re-vegetation attempts to identify the rate at which a newly denuded (bare) bank will at first erode and subsequently attain stability due to the seasonal re-growth of vegetation. In effect, the question addressed is 'can nature heal its own wounds in a short period of time without the assistance of man '? As mentioned in 1.1 this is a recommended non-structural mode of bank stabilization. The short duration of this experiment (24 months) is relevant in that aspect because it is normally a period of one to two years which will be the interval between major floods. As such any plants that colonise the bank should, in theory enhance the bank stability before the next floods. If they fail then the plants themselves may be washed away.

In essence, one would expect the following properties from the initial colonisers in the initial stages of succession on a bare bank of a waterway :-

i. fragments of roots and rhizomes that alight mostly at the toe-region of the bank should establish a new plant or colony ;

- ii. seeds that either alight on the bare bank or resident seeds that have survived the systemic herbicide treatment should germinate rapidly, to prevent wash out either from precipitation run-off down the bank slope or due to changing hydrograph;
- iii. seedlings should root and establish rapidly thereby anchoring the plant on to the bank soil;
- iv. once the root system is established, the shoot system that grows must offer the least possible resistive surface area to the motive force of the water, for its own survival from being eroded in the fluvial process; any morphological adaptive mechanisms that enhance survival of the plant would be useful;
- v. the ability of a plant to cover the bare ground with foliage (leaf area ratio) may prevent surficial erosion of the soil surrounding the base of the plant;

Secondary succession or gap colonisation is associated with changes in species composition over long periods of decades to a few centuries until it reaches its climax vegetation (Odum, 1953). In this experiment the study of succession is limited to changes within the first two years since artificial denudation of the banks. While stages 1 to 5 of Clements' phases are present with 'pioneer colonisers' over two growing seasons, this study period does not wholly address the long-term interactions between species.

The main theme of this experiment was to study variations of erosion rates under early secondary succession of a bank while observing the species diversity and pattern of establishment. Therefore, the study of succession was limited to observations of qualitative changes (i.e species establishment) than quantitative (seedling density) changes. The latter would be required if this study addresses succession from a quantitative ecological aspect such as population dynamics or correlations and associations (see. Kershaw, 1980). Formulation of such major research studies may depend on the outcome of this study on the question of the ability of the initial colonisers (i.e. succession over two growing seasons) to arrest the process of erosion of the bank. In this study, the capabilities of pioneer colonisers in stabilising the bank soil during the process of their establishment was assessed based on the quantification of erosion of the bank on which they colonised. Whether they will be the same climax species such as *U. dioica* or *E. hirsutum* or the grasses as observed in 2.2.1f, was unknown at the

commencement of the experiment. If they were different species from those constituents of the climax community and they could reduce erosion to levels comparable to that of the climax community (see: 5.4.2e, 5.4.2f and 5.4.2g below), then it should prove that these colonisers have the adaptive capability to not only establish themselves on an eroding bare bank which may be subjected to stresses of changing hydrographs but conserve the bank soil as well. Whether these species are competed out by other invaders who may form a climax community consequently is more an ecologically oriented question than one of geomorphological significance.

In essence, the main questions are :

- a) can the pioneer colonisers arrest the process of erosion ?
- b) what species are they ?

5.2. Aims of the experiment

- i. to quantify erosion of a previously devegetated bank which was subsequently naturally re-vegetated (i.e. mainly by seed propagule establishment and colonisation of different species as the initial steps of secondary succession), for different flow regimes that occur through the period of experimentation
- ii. to compare the respective rates of erosion of a bare bank, with that of a naturally re-vegetated bank for different flow regimes that occur through the period of experimentation (25 months);
- iii. to compare the respective rates of erosion of a naturally vegetated (i.e. normal vegetation as existant in other parts of the bank established over 15 years) with a bank in the process of secondary succession following total denudation at some stage, for different flow regimes that occur through the period of experimentation (25 months);
- v. to compare the rates of erosion at ambient flow under a naturally vegetated bank and a naturally re-vegetated bank with special reference to the corrasion in higher moisture, toe region (0 to 0.75m from base);
- vi. to compare the rates of erosion between the drier upper region in naturally re-vegetated bank with the wet narrow band off the bank toe region;
- vii. to study the re-vegetation pattern on the banks in terms of establishment of species of plants over the two years of experimentation;

viii. to compare the performance of naturally re-vegetated banks with special reference to *P. arundinacea* as a cultivated comparable cohort from seeds on a bare bank.

5.3. Experimental Plots

4a, 4b, 10a, 10b, 13a, 13b were the plots under this study of natural re-vegetation as shown in Figure 2.2.

The erosion measurements used for comparisons were those of :

Bare Banks : Plots 1a, 1b, 7a, 7b, 12a and 12b;

Naturally Vegetated banks : 3a, 3b, 6a, 6b, 14a and 14b;

Phalaris arundinacea cultivated plots : 2a, 2b, 9a, 9b, 15a and 15b.

5.3.1 Preparation of Plots

The plots were devegetated in June 1986 by spraying the systemic herbicide "Round Up" as described with details in section 2.3.2, earlier. Consequent to this total devegetation in June 1986, there were no further attempts at devegetation throughout the period of experimentation.

The main comparison of erosion was on erosion measurements in relation to the Bare plots which were kept bare by frequent 'spot application' of herbicides throughout the period of experimentation. Whereas the Bare plots 1a, 1b, 7a, 7b, 10a, 10b, were exposed to the natural processess of weathering, rainfall and fluvial erosion, the plots for natural re-vegetation were left intact with the dead foliage resulting from the herbicide application forming a covering for the soil on these plots (see Plate 9). This was an attempt to simulate an application of systemic herbicide as practised by some farmers where the dead litter may not be cleared. Such a semi-natural process may allow healthy conditions of establishment of vegetative propagules alighting in these plots. Propagules of seeds will germinate under such ideal micro-climates of humidity and light spectral characteristics. Certain other species may not be successful in establishment under these conditions.

5.3.2 Field Measurements

The methods adopted have been described with the appropriate reasons in Ch.2. The measurement regimes were as follows:

- a) Periodic erosion (mm) (see 2.4.1) in each of six plots 4a, 4b, 10a, 10b 13a, and 13b (Fig.2.3);
- b) Recording of species establishment : April and September 1987 and May 1988. This was carried out for plots 10a, 10b, 13a and 13b (see: Fig. 2.3). The positions at which the species established were recorded on the three occasions as shown in Fig. 5a below :

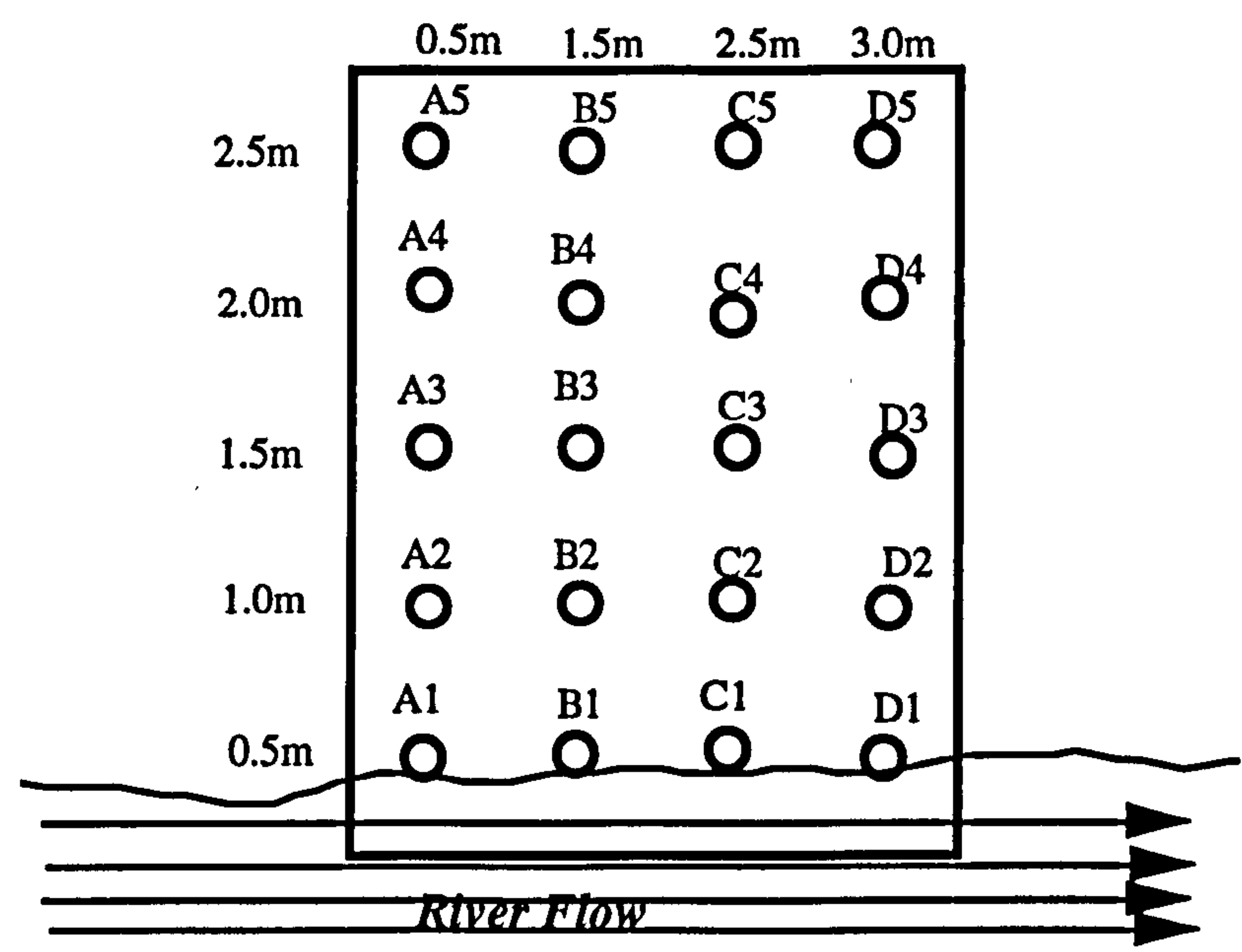


Fig. 5a Positions of survey of colonising species of naturally re-vegetated plots;
(See Appendix 7a-7c for details)

Kershaw (1958) developed a point quadrat for taking contiguous cover readings along a transect which utilises a pin to note the presence or absence of a species in a situation such as a grassland. The problem with a sloping river bank with micro-topographic variations is that such an equipment is not practical. Therefore, it was decided that the nearest individual plant up to 5cm upwards from the marker pin positions A1 to A5, B1 to B5, C1 to C5, and D1to D5 (Fig. 5a) on the four plots be identified. The results are given in Appendix 7. The data are discussed in 5.5 later.

5.4 Results and Analysis of Data

5.4.1 Results

consisted of four main sets of recordings; They were:

- a) Erosion measurements over 24 months;
 - c) Daily hydraulic discharge near the site (l/s)
 - d) species established on the bank at the grid positions over the two years;
- (summarised data are presented in Appendix 3, 4 and 7)

5.4.2 Analysis of data

The analysis was carried out in keeping with the aims of the experiment as set out in 5.2.above. Statistical analysis is described in 2.8.

5.4.2a Comparison of erosion of Bare versus Naturally re-vegetated banks (whole banks) (see Fig.5.1)

a) Phase 1 As the banks were de-vegetated with a systemic herbicide in June 1986, there was sufficient time for the re-generation process of vegetation by August 1986. An important fact is that the erosion of these banks from June to December 1986 (Phase 1) are less than that of the bare banks because the former had its dead foliage intact and covering the topsoil of the bank (see Plate 9). An analysis of variance for this period shows a significant difference ($F = 5.978$; probability = 0.0346). Mulch cover has been found to reduce erosion of hillside lands such as those on tea plantations (Krishnarajah, 1985). The reason may be the dead foliage acting as a cover to prevent rain splash erosion of the topsoil for the rains during this period.

b) Phase 2 Erosion during Phase 2, was similar to the Bare banks. Analysis of variance indicates a probability of 0.5011 ($F = 0.487$).

The following are proposed as the reasons for similar erosion during this period:

- a) by February 1987 the initial process of top soil erosion in the bare plots had exposed the less erodible soil layers underneath ;
- b) by February 1987 the first flood did clear much of the dead vegetation cover from the 'naturally re-vegetated' plots thereby exposing its topsoil to the first major period of erosion. Hence the delayed erosion;
- c) the extent and depths of rooting on the top-soil of the naturally re-vegetating banks were low; while these were sufficient to withstand total wash away by corrasion or slumping in the first major incidence of flood in December to January 1987, the banks

were weakened by the saturation. This led to wet-bank slumping in the fluctuating flow conditions in the ensuing months. As such a major question arises as to the suitability of the suggested non-structural measure of natural stabilization (see 1.1 and Table 1.1) of an eroding river bank during the ambient flow regimes.

It is not feasible to suggest this measure if we are to arrive at conclusions from the results of Phases 1 and 2 of this experiment. One must bear in mind that devegetation was carried out in June and the banks had a natural re-establishment period of only five months prior to the first winter floods. Of these, the first two months cannot be counted as conducive to natural establishment of any plants due to the severity of the active ingredient in the herbicide application. As such we are interpreting the effects of natural re-vegetation effects over eight weeks between August and September beyond which (October onwards) the possibility of seedling establishment or vegetative reproduction from root proliferation from adjacent vegetated areas is minimal. Phase 3 offers a better length of time and normally conducive periods for the establishment of a range of naturally-revegetating species over a full Spring and Summer. Further conclusions are :

- i) mulch cover left intact on banks devegetated with a systemic herbicide helps to reduce bank erodibility through the first floods;
- ii) consequent to the wash out or decay of the mulch cover the erodibility of the exposed soil increases compared with that of a bank which had its dead vegetation removed after the application of the herbicide.

c) Phase 3 (April to September 1987): Contrary to what was expected the first full summer's growth of vegetation did not reduce the rate of erosion to negligible levels (see Fig. 5.1). However an analysis of variance shows that there is a significant difference, (at $< 5\%$) between the erosion of Bare banks and naturally re-vegetated banks during this period ($p = 0.03585$; $F = 5.674$). While these plots were being recolonised by a host of species the percentage ground cover was low as the plant establishment was skewed in spatial distribution. The result was surficial erosion during precipitation and corrosion

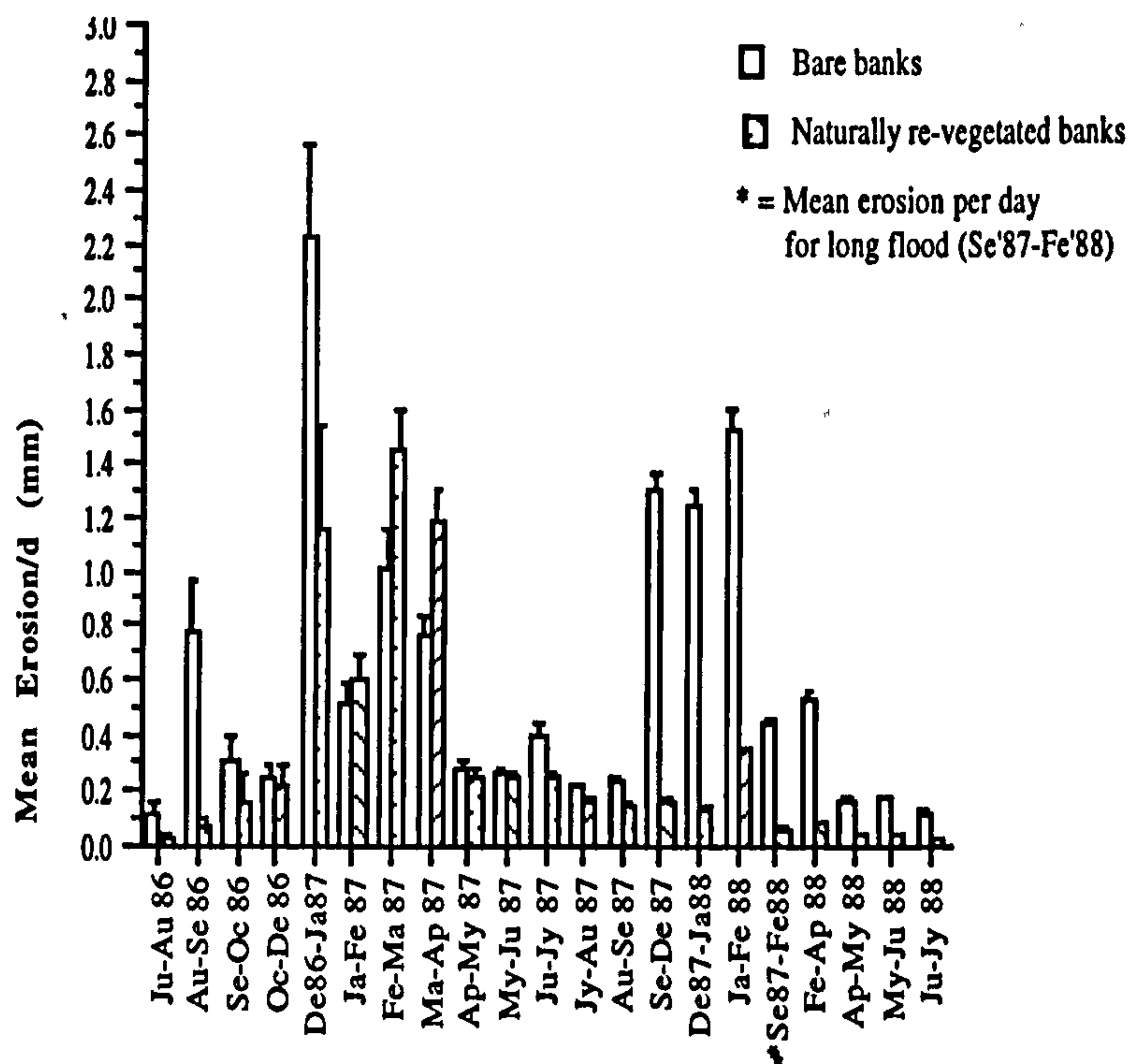
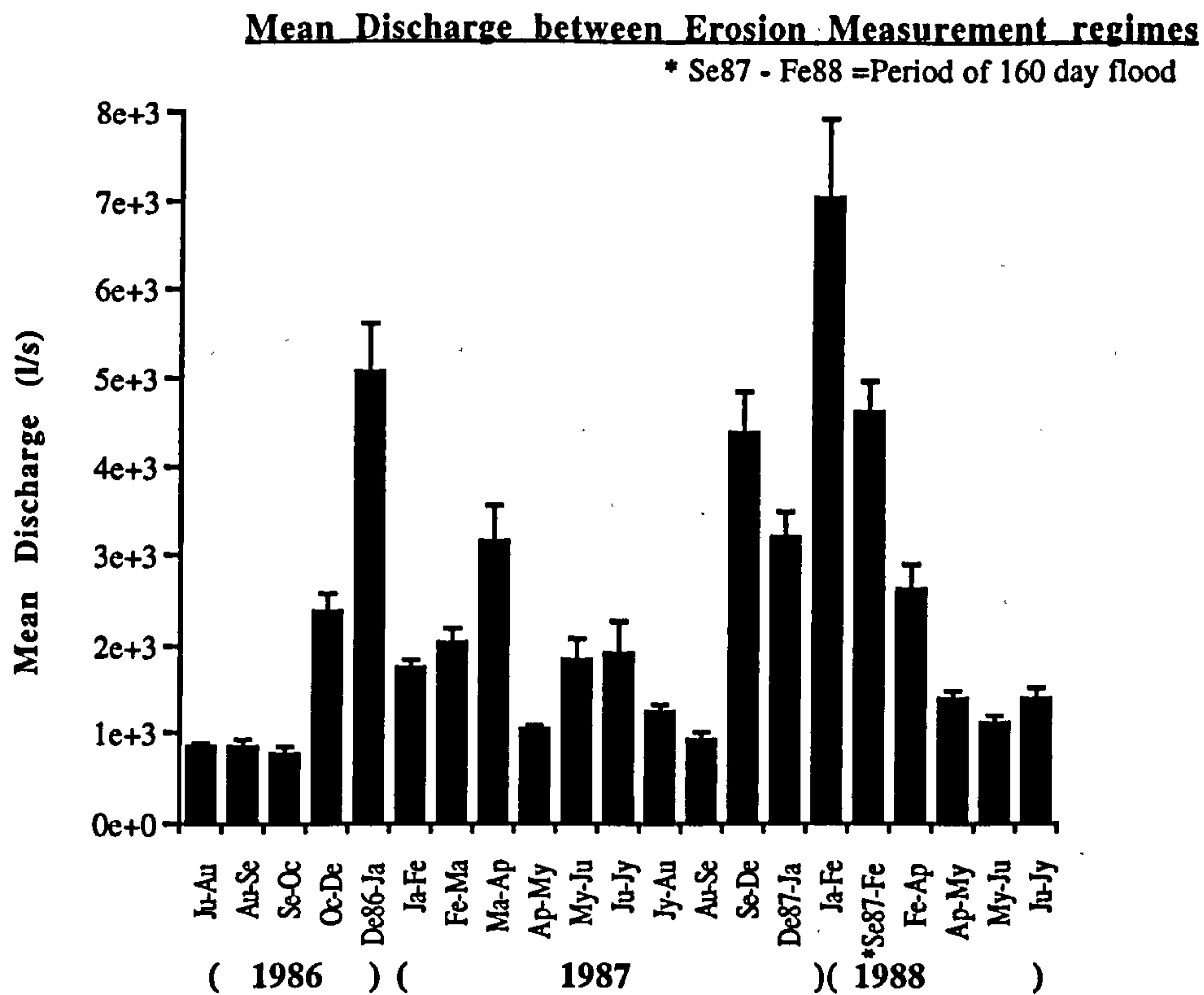


Fig. 5.1 : Comparison of erosion : Bare soil Vs. Natural re-vegetation (whole banks)

during the frequently changing rise and fall of the river hydrograph (see Figs. 3.1a and 5.1). The conclusion is that natural re-vegetation as a non-structural means of bank stabilisation may not be recommended under conditions of a changing channel hydrograph and precipitation even if all other seasonal parameters are conducive to natural establishment of vegetation in secondary succession on a disturbed/ devegetated bank. This conclusion will have particular relevance to irrigation canals in tropical countries.

d) Phase 4 (September 1987 to February 1988): By the end of Phase 3 re-vegetation had been so effective that even with the severe and prolonged flood of October 1987 to January 1988 the bank erosion was reduced to very low amounts on naturally re-vegetated banks as compared with the Bare banks (see Fig. 5.1). Analysis of variance between the Bare banks and naturally re-vegetated banks indicates a very highly significant difference ($p = 1.0000E-4$; $F = 138.804$) The question arises as to how a fast colonising natural re-vegetation was not so effective during the summer but is extremely effective under a severe and prolonged flood event that follows the Summer. The explanation may lie with the observations on the forms of erosion that occurred during the two periods. As mentioned in Phase 3, summer erosion was corrosion of the top soil by frequent but short term changes in the river hydrograph in addition to surficial erosion of exposed, uncolonised bare patches of soil by precipitation and surface runoff. During Phase 4 the erosive process was more of wet-bank slumping than corrosion.

The crucial difference is that while corrosion did occur during Phase 4, slumping (which accounted for the major aspect of Bare bank erosion), was prevented in the naturally re-vegetated banks because the newly established plants had established an extensive root-system over the summer thereby 'consolidating' the banks against slumping under either high fluvial forces or under conditions conducive to wet-bank slumping. Root sampling was not carried out within the naturally re-vegetating plots because (a) the recolonisation pattern was random rather than uniform in the early stages (see Plate 9) and (b) in order to minimise disturbing the soil under newly emergent seedlings and young herbs. However, the survey of colonising species (see App.7b) amply illustrate the species that colonised the banks during this period. *Rumex spp.*, *Cirsium spp.*, *Plantago spp.* as well as the grasses such as *Poa spp.*, and *Glyceria spp.*,

are well known as deep-rooting colonisers. In addition one is referred to Plates 9, 10 and 11 as evidence of the fast re-colonisation of a devegetated plot from first summer (Plate 9, approximately four months after application of herbicide) to the third summer (Plate 10, early 2nd summer to Plate 11, late 2nd summer). (N.B. the word 'consolidation' of the bank soil is considered more appropriate to this study as it is controversial to allocate the effects of increased root density to increase in shear strength of the bank. Therefore it has to be concluded that natural re-vegetation is efficient to prevent slumping of banks under storm flows or flooding.

e) Phase 5 second summer erosion within treatments (April to August 1988):

As shown in Fig. 5.1 there has been a highly significant reduction in erosion in this period. Statistically the difference in erosion is highly significant ($p=1.0000E-4$; $F=80.016$). The renewed growth and colonisation by resident and immigrant species during the spring and early summer has contributed to this reduction in erosion.

Conclusions:

1. The physical barrier caused by the dead vegetation left intact on the banks contributes to significant reduction of bank erosion under fluvial inundation.
2. Once the debris is washed away, the exposed banks erode until ground cover is established as a result of new coloniser species.

5.4.2b Comparison of erosion of Bare banks versus Naturally re-vegetated banks (Upper banks) (Fig. 5.2)

a) Phase 1 (See Fig. 5.2) The initial significant differences in the mean erosion rates (June to August, August to September and September to October 1986) between the two treatments are a result of the effects of leaving the dead vegetation intact on the plots allocated for natural re-vegetation as opposed to removal of all dead vegetation exposing the bare banks for the Bare soil treatment. The comments made, with reference to slumping and associated physical properties of the banks, in 5.4.2a (Phase 1) apply equally to the upper banks.

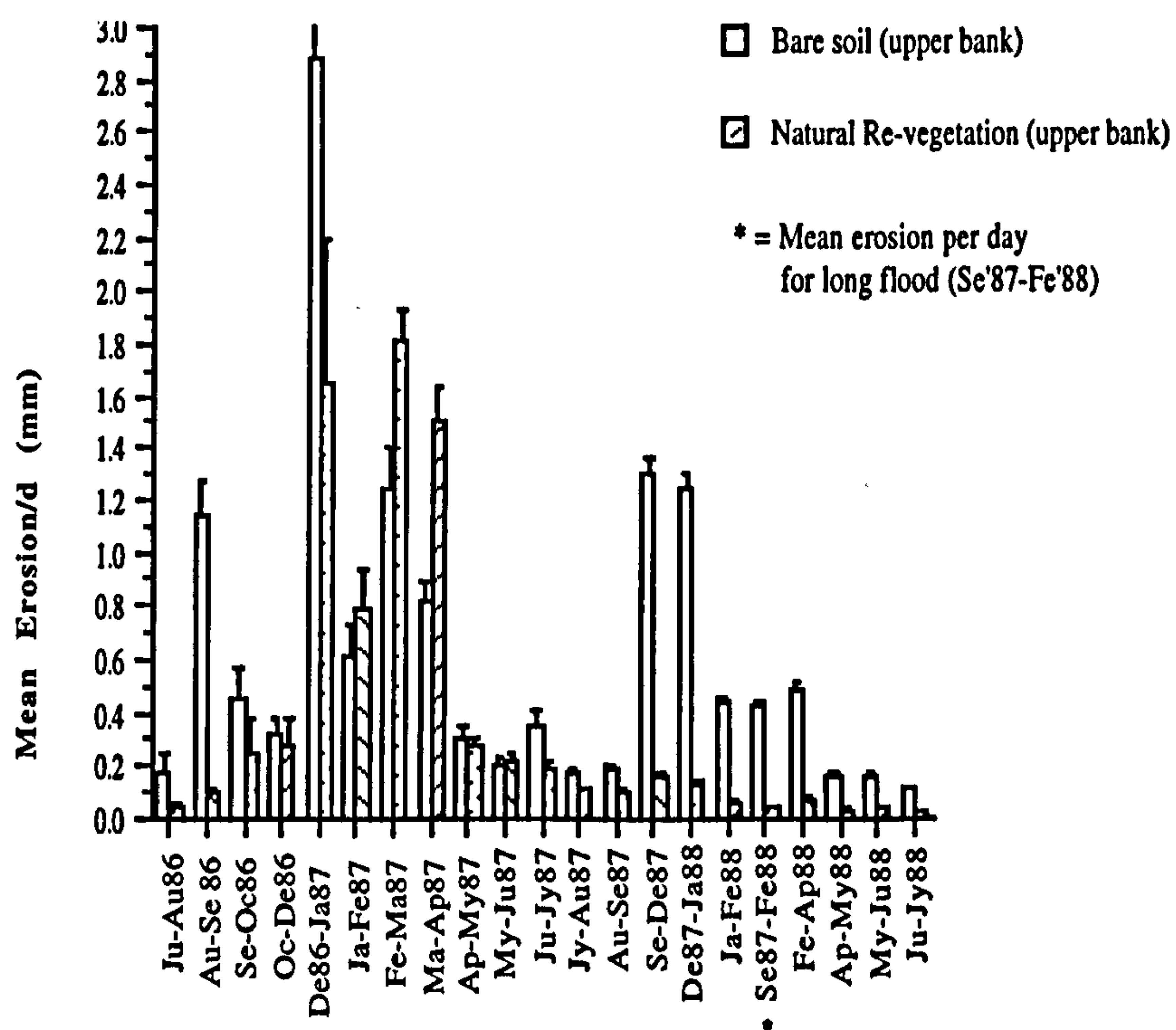
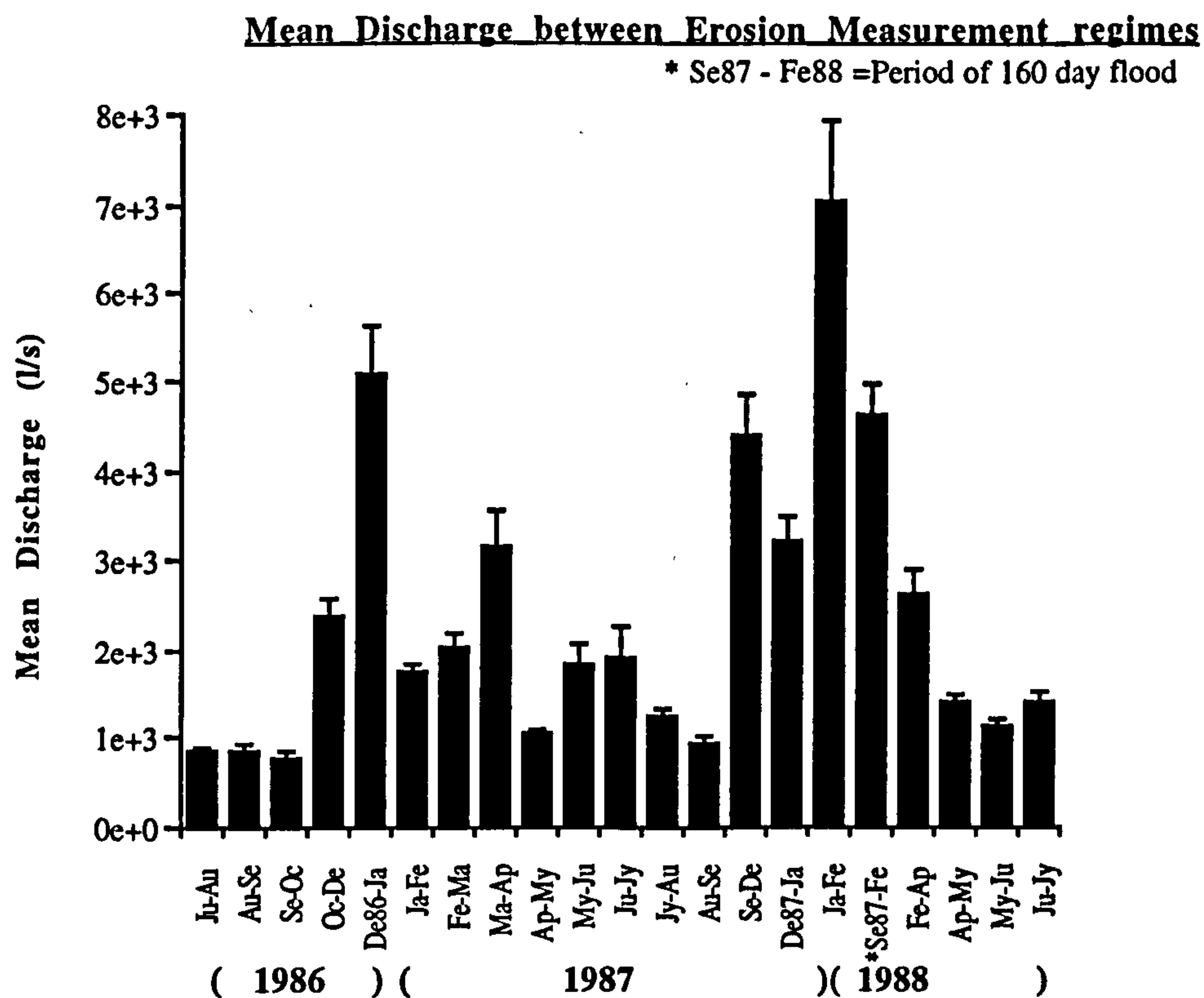


Fig.5.2 : Comparison of Erosion : Bare soil vs. Naturally Re-vegetated banks; (upper bank)

What is noteworthy is the difference in the rates of increase and decrease of bank erosion between the two treatments within the first six months of application of the systemic herbicide. There is a sudden increase of erosion (August to September 1986, $1.1425 \pm 0.135\text{mm/d}$) for the Bare banks (as opposed to $0.989 \pm 0.0193\text{mm/d}$ for Normal vegetation) associated mainly with dry-bank slumping. It must be noted that this process commences with a sudden and considerable increase in erosion within two months after the application of the systemic herbicide. Thereupon the rates of erosion decrease as the more stable lower layers of the top soil are exposed to weathering and precipitation rather than any hydrographic changes up to the first major flood incidence of December 1986 to January 1987. On the contrary, the plots allocated for natural re-vegetation (which are covered with the dead vegetation on top) do not undergo a sudden increase of erosion at the same time as the totally Bare banks. What happened was that the mulch cover not only prevented rain splash and surface runoff but also delayed the weathering of the top soil thereby delaying the process of slumping. In the ensuing months there was continuous increase in the top soil slumping until by December 1986 both treatments show almost the same amounts of erodibility. This shows that leaving the dead vegetation intact on the soil surface delays the process of bank weathering. But, beyond this critical period (in this case June to September = 3 months, at ambient river flow) it is subject to an increasing process of erosion mainly by slumping of top soil in patches. However cumulative erosion for this treatment for Phase 1 was lower than the Bare plots as the patches of banks being colonised by the re-vegetation (especially Levels 2 and 3) did not erode as much as the uncolonised areas.

b) Phase 2 The lower rate of erosion for the plots allocated for natural re-vegetation, in the December 1986 to January 1987 flood period, was a consequence of both the revegetating patches and the remnants of the dead vegetation as opposed to the absence of both these aspects in the Bare banks. However, the continuous high flow conditions with the fluctuations of the hydrograph, washed off the dead vegetation and increased the wetness of the upper bank above normal levels. The result was that the loosened exposed soil continues both corrosion and meso-scale slumping. The latter process exacerbated the erosion as the shallow rooted plants tended to wash away with their root-adhered patches

of soil. Hence we see the higher erosion rates for the plots allocated for natural re-vegetation ($1,807 \pm 0.123$ for February to March 1987 and 1.509 ± 0.125 for March to April 1987).

c) Phase 3 With the onset of Spring growth and establishment of plants the increase of soil erosion is arrested. But, the reductions in the rates of erosion are not significant until after the advent of Summer, (June 1987; see Fig. 5.4). It is concluded that erosion rates are minimal during this phase. In fact Bare banks have minimal erosion in summer as proven by other authors.

d) Phase 4 The most interesting aspect and the crucial test of this experiment was during Phase 4.

(Phase 4) Comparison of Mean Erosion rates (mm/d)

Mth/Year	Bare/U	S.E./d(B)	Re-veg/U	S.E./D(R)
Se-De 87	1.3000	0.0588	0.1653	0.0090
De87-Ja88	1.2489	0.0490	0.1300	0.0116
Ja-Fe 88	0.4323	0.0268	0.0657	0.0079
*Se87-Fe88	0.4271	0.0157	0.0487	0.0024
Fe-Ap 88	0.4860	0.0244	0.0790	0.0056

It is obvious that the reduction of erosion rates are considerable in the upper banks of a naturally re-vegetated bank when compared with a similar bank kept bare (see Fig. 5.2 and Plate 4).

e) Phase 5 By the second summer Summer erosion rates were negligible for the upper banks of the Naturally revegetated plots, while active erosion was in excess of sevenfold of that in the Normal vegetation plots.

Conclusions

The conclusions made for the whole banks (5.4.2a) apply in the comparison of the upper banks. The presence or absence of the dead debris on a systemically devegetated bank decides the short and long-term erodibility of the bank.

5.4.2c Comparison of erosion of Bare versus Naturally re-vegetated banks (Lower bank) (Fig.5.3)

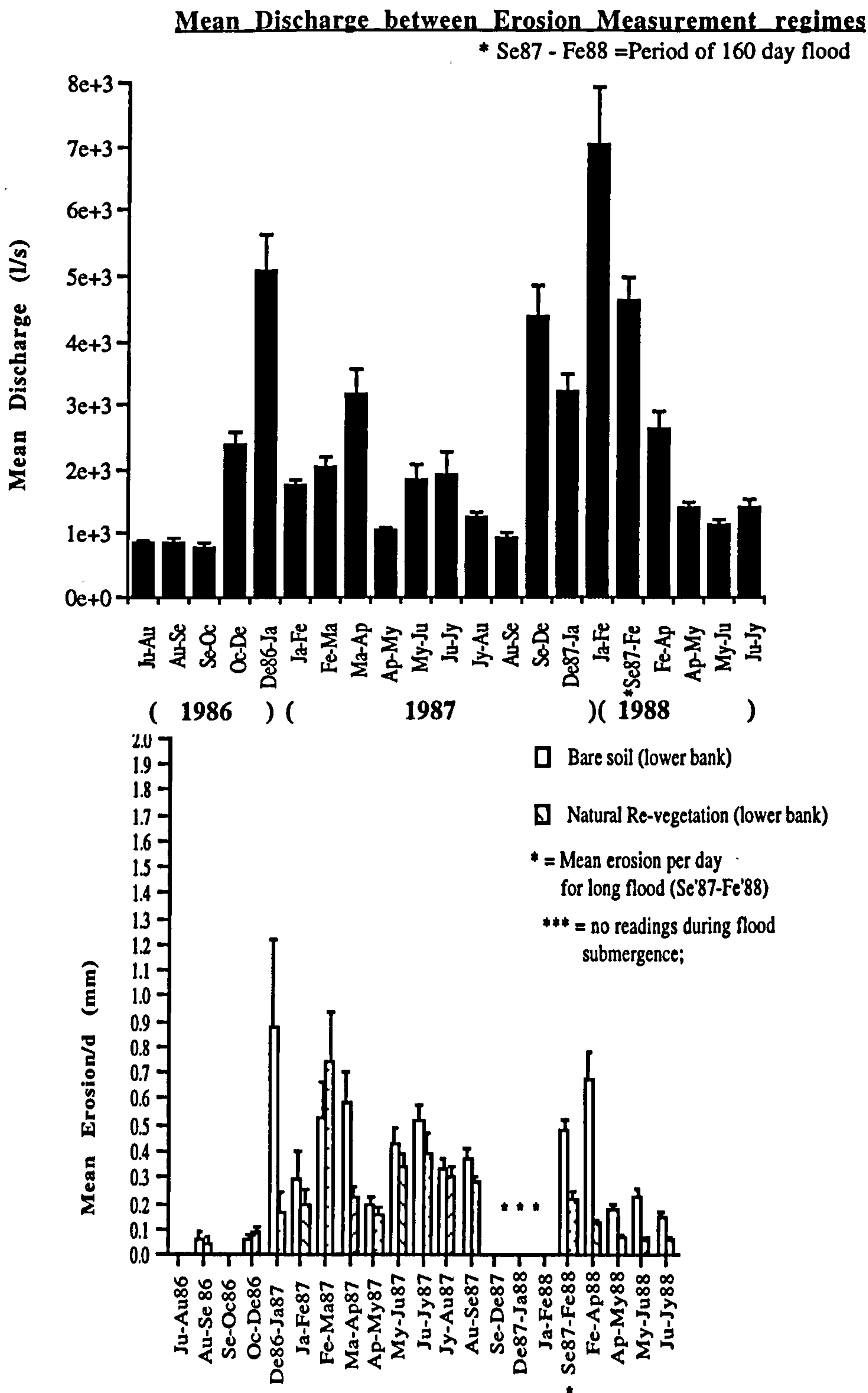


Fig.5.3 : Comparison of Erosion : Bare soil Vs. Naturally Re-vegetated banks; (lower banks)

a) Phase 1 The effect of dead vegetation cover on the banks is reflected in the lower rates of erosion for the lower banks allocated for natural re-vegetation. Note the newly emergent vegetation at the bank toe-region in Plate 9. Compare this with the complete absence of such fringe vegetation in the long established natural vegetation in Plate 5.

The reason for the vigorous growth in the toe-region of the devegetated patch is the availability of niche space which is open (not shaded as in the long established vegetation banks).

The other observation of importance in reduction of erosion of this area is the orientation of the dead vegetation and debris onto the lower bank from the upper banks. This offers a physical barrier between the bank soil and the flowing water thereby reducing erosion in this region.

b) Phase 2 (December 1986 to April 1987); There is significantly less erodibility for the re-vegetated plots than those of the bare banks during the first high flow period of December 1986 to February 1987 (the winter of 1986/7). This is due to the establishment of the newly colonising species in this region. But in the post-flood period (February to March 1987) there is unusually high erosion ($0.74\text{mm}^{-\text{d}}$) which is unaccountable either in relation to flow variations or any known factor associated with plants. Whether incidences of frost leading to death of the young plants and/or frost heave is associated with the high rates of erosion are unclear as this study did not encompass this aspect of erosion.

c) Phase 3 (April to October 1987); During the second summer lower bank erosion of the naturally re-vegetated plots were less than those of the bare banks (see Appendix 4b) This is because there was limited but definitive colonisation of the toe-region (see Appendix 7b) by any naturally re-vegetating species. The conclusion is that natural re-vegetation of the bank-toe region is prevented by a frequently changing channel hydrograph. As such it needs special control of the channel flow for a long period under ambient flow conditions, if natural re-vegetation of this region is to be encouraged as a short-term measure of natural, yet accelerated and effective reduction of erosion.

d) Phase 4 Only mean rates of erosion per day calculated from the cumulative erosion for the four months of submergence are available as shown for September 1987 to February 1988 (Fig. 5.3). On the whole whether this is simply a continuation of the increasing efficiency of the lower bank (see : end of Phase 3 in Fig. 5.3) or a reflection of any effects of roots from Level 2 reaching this region by this period as a means of consolidating the bank-toe is unclear.

e) Phase 5 The second summer is associated with significant reductions in rates of erosion of the naturally re-vegetated banks as compared with the actively eroding bare banks as seen in Fig.5.3.

Conclusions

The process of devegetation (of a previously long-established bank vegetation) is followed by secondary successional processes of particular significance to the lower bank in particular and in turn to the stability of the whole bank. They are:

i. the colonisation and emergence of new species adapted to colonise the bank from the toe-region upwards to the apex of the bank. The main reason for this is the availability of a space (as a resource) with light and moisture content suitable for new seedling establishment and vigorous growth. The critical factor that initiated this process is the "unshading" of the lower bank by herbicide defoliation of the upper banks thereby removing the overhang vegetation similar to that shown in Plates 6 and 7.

ii. The process of secondary succession and erosion of a river bank is spatially and temporally guided by the following stepwise phenomena:

- a) colonisation by grasses and seedlings at the bank toe-region as shown in Plate 9;
- b) vigorous establishment and growth of *Rumex spp.* through the grasses in the high moisture content areas as shown in close view in Plate 12 and the data on Appendices 7a to 7c);
- c) establishment of diverse vegetation on the upper regions as in Plates 10 and 11 (see data on Appendices 7a to 7c);

The significance of this bank-toe to apex sequential pattern of colonisation are:

- a) the initial toe-colonisers form a physical barrier between the flow and the bank thereby preventing erosion of this region;

- b) the initial toe-colonisers form a physical barrier that accumulates any debris and eroding soil from the upper banks that are eroding due to sparse revegetation;
- c) the build up of silt from the base upwards to apex of the bank encourages establishment of species in the upper banks and hence consolidation of the upper banks;

At the outset of this experiment a process oriented hypothesis (whether secondary succession will be uniform throughout the banks or a toe to apex process or vice versa) was not proposed. However, the results observations and the discussion highlight the existence of such a spatially oriented pattern of secondary succession.

The value of this observation lies in (a) the theoretical understanding how natural systems repair/readjust themselves when subject to a temporary imbalance (i.e. artificial denudation and hence bank erosion or active fluvial erosion under intense channel flows) and (b) the applicable implications in river corridor dynamics with geomorphic significance.

N.B. The alternative hypothesis is a bank-apex to bank-toe process of spatial colonisation over a given temporal phase. It is theoretically non-feasible as such a process would encourage basal bank erosion and in turn pseudo-cyclic erosion patterns proposed by Knighton (1984).

5.4.2d Comparison of erosion within naturally re-vegetating banks (upper versus lower banks) (Fig. 5.4)

a) Phase 1 initial period of low flow (June to December 1986); The result of the herbicide application on natural vegetation is death of its roots and shoots. As the roots die the soil instability is reflected by the appearance of surficial cracks especially at Levels 2 and 3.

After the first 2 to 3 months (from August 1986, see Fig. 5.4) the upper bank covered with the dead vegetation, commences the process of dry-bank slumping of the top soil in patches. It increases over the next few months although the flow conditions are ambient. As the toe-region did not have much vegetation, it has not been affected by the

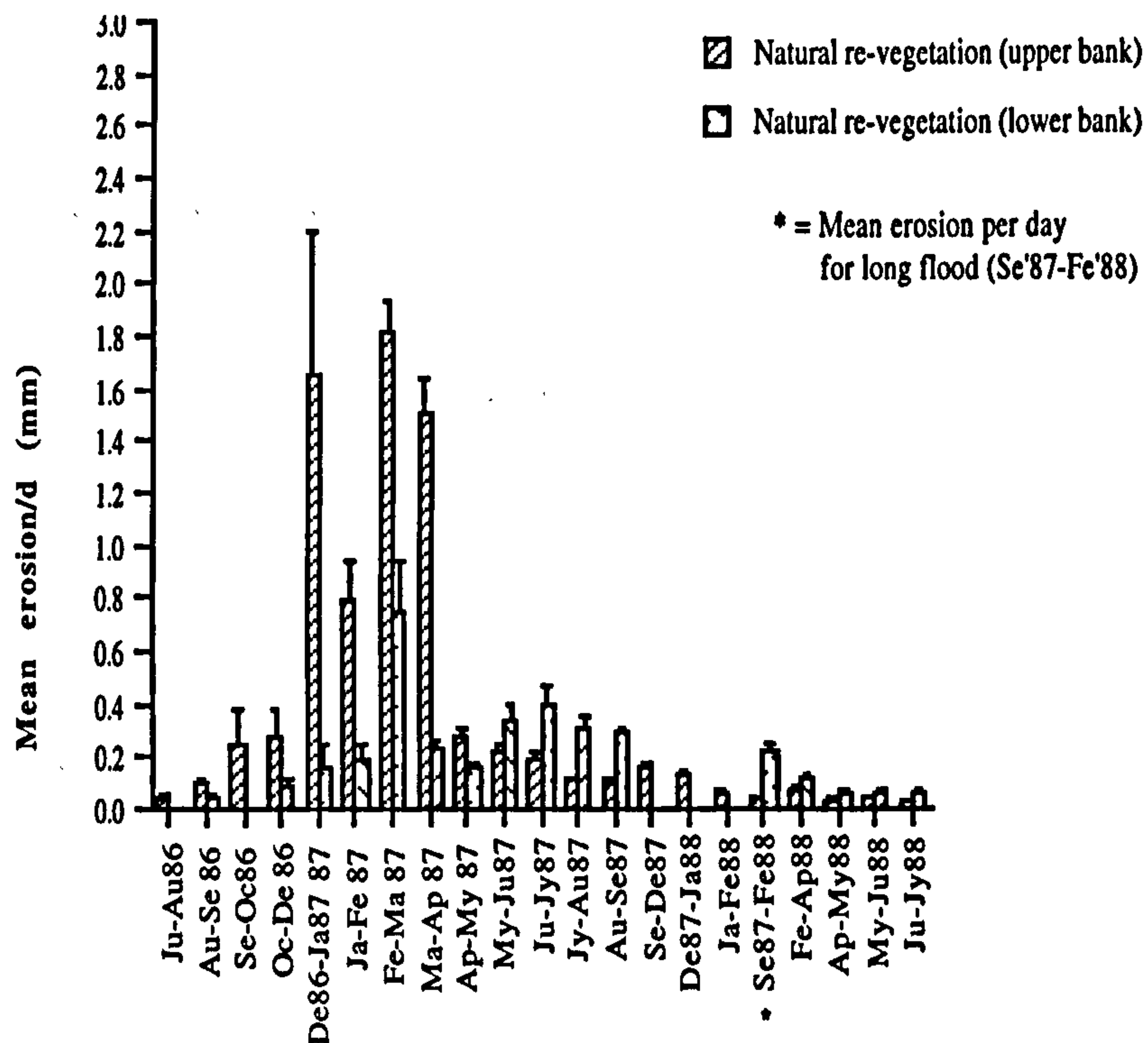
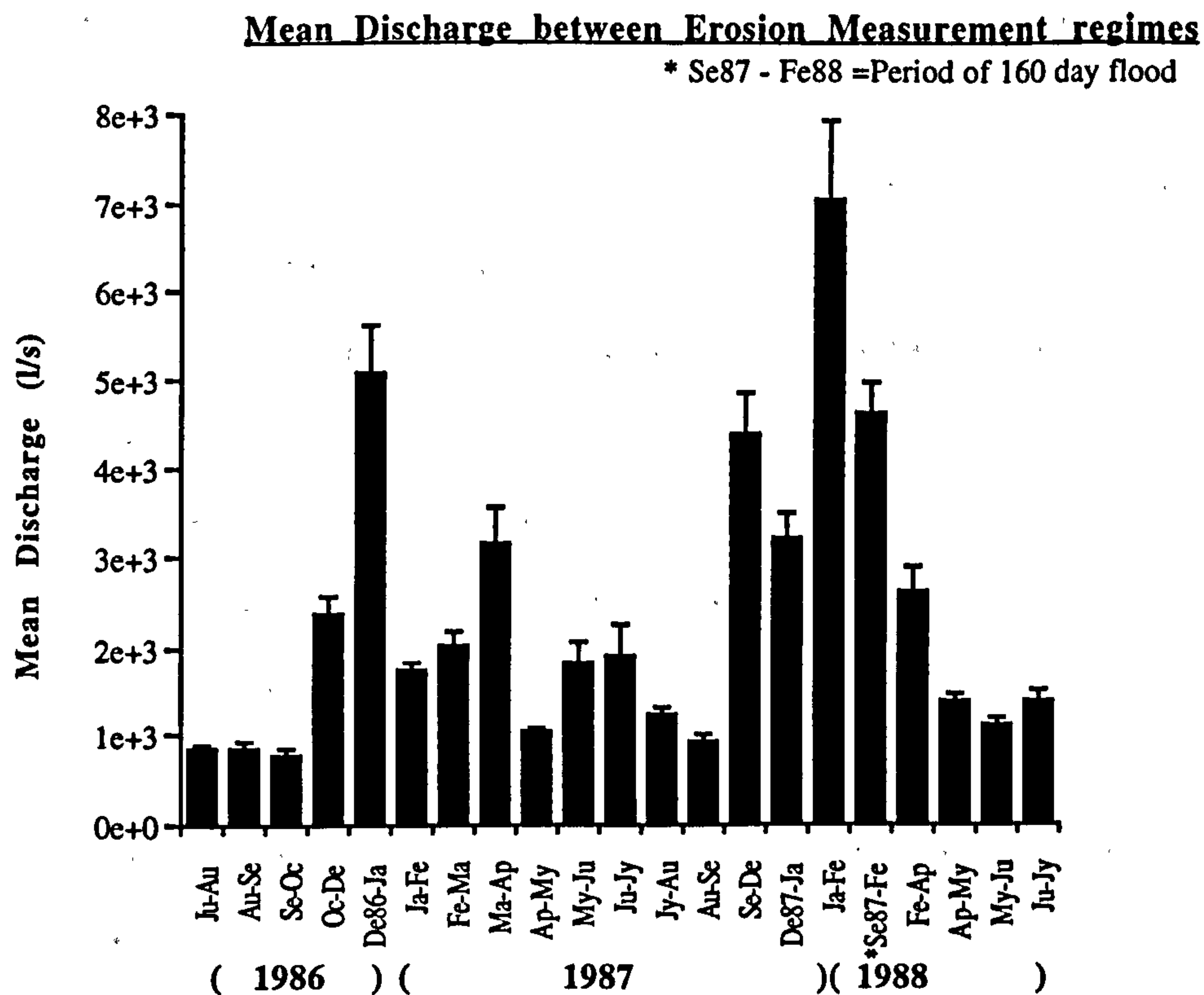


Fig. 5.4 : Comparison of erosion : Upper Vs. Lower banks within Naturally re-vegetated banks

systemic herbicide application. The result is that it has lower rates of erosion in comparison with the upper bank.

b) Phase 2 There is very high upper bank erosion during the first floods after denudation. It is in keeping with the processes of gradual but steady upper bank destability with time as a result of artificial denudation. The considerable increase in upper bank erosion in Phase 2 does indicate that there was potential for very high erodibility during Phase 1. But the reason for its temporary stability is more due to the absence of an increase of the river hydrograph during Phase 1 than a true stability arising from bank soil properties such as shear strength.

The lower banks do erode during phase 2 at much reduced rates when compared with the upper banks. As the fluvial forces are higher in magnitude at the base of the bank than the upper layers at bankfull flow, it is this level which should have eroded more if there had been any destability caused by the application of the systemic herbicide.

c) Phase 3 Lower bank erosion fluctuates at minimal levels (c. $0.2\text{mm}^{-\text{d}}$) for the lower banks in comparison with minute levels (c. $0.05\text{mm}^{-\text{d}}$) for the upper banks as seen Figure 5.4.

The difference is due to the much higher colonisation of the upper banks (Levels 2, 3 and 4) than the lower banks (Level 1) during the Summer (see Appendix 7b). The reason for the lack of colonisation of Level 1 was the regular fluctuations of the river hydrograph throughout the Summer thereby preventing the establishment of floating down pieces of roots and stems as a means of vegetative reproduction or seedlings.

d) Phase 4 There are no individual erosion rates for the lower banks during the long flood period. As such the only comparison that can be made is the mean erosion rate calculated from the accumulated erosion for this period. The mean erosion rates per day are again minimal (c. $0.05\text{mm}^{-\text{d}}$) for the upper banks which were naturally re-vegetated over the previous Summer (Phase 3) while the lower banks erosion rates are much higher (c. $0.25\text{mm}^{-\text{d}}$). These higher rates of toe-region erosion are due to lack of establishment of fringe vegetation, as mentioned for Phase 3 above, and the higher erosive forces during the floods at this region.

e) Phase 5 By this period the re-vegetation process had reached highly satisfactory (uniform vegetation cover, variety of species) progress on the upper banks (see Appendix

7c). As such erosion was minimal in the upper region. As the river hydrograph for this summer was low there was hardly any toe region erosion.

Conclusions

The discussion and conclusions in 5.4.2c apply for 5.4.2d as well.

5.4.2e Comparison of erosion of Naturally vegetated banks and newly re-vegetating banks (whole banks) (Fig.5.5)

a) Phases 1 and 2 (June to April 1987); As expected, high erosion is prevalent within the plots allocated for natural re-vegetation as opposed to the minimal erosion rates for the long established naturally vegetated banks during both phases of initial ambient flows and subsequent first winter flows.

c) Phase 3 (April to October 1987); Summer erosion is gradually retarding in the newly re-colonising treatment.

d) Phase 4 (October 1987 to April 1988; a winter of early storm flows and long duration):

There is a higher erosion rate of whole banks of naturally re-vegetated as compared to the long established naturally vegetated banks. This may be due to the non-uniform nature of vegetation cover in the early process of pioneer colonisation (see Plate 11). **e) Phase 5**

(April to August 1988) second summer erosion within treatments. By the middle of the second summer (July 1988) the naturally re-vegetating banks have reached almost similar magnitudes of low rates of erosion to the long established naturally vegetated banks.

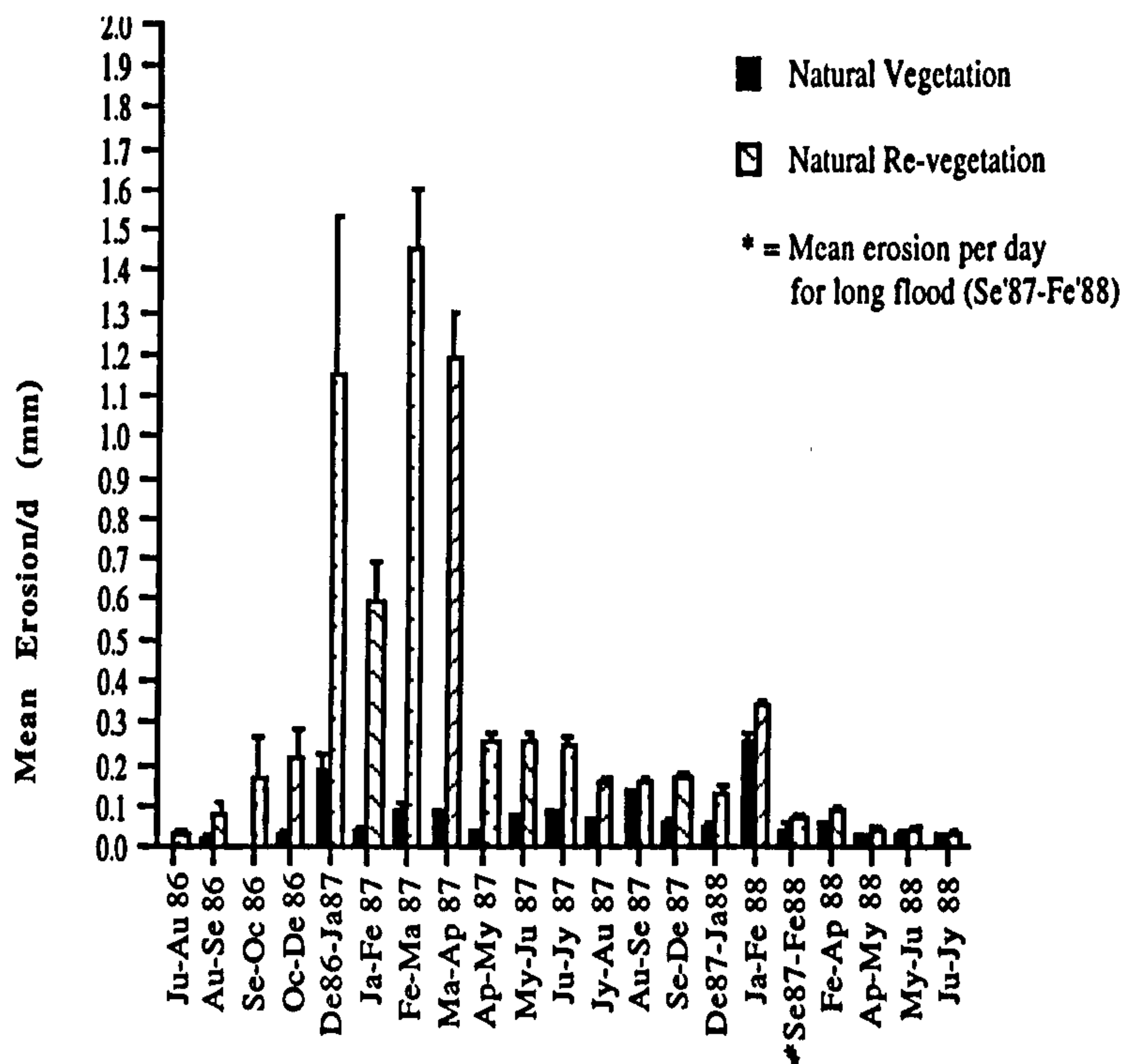
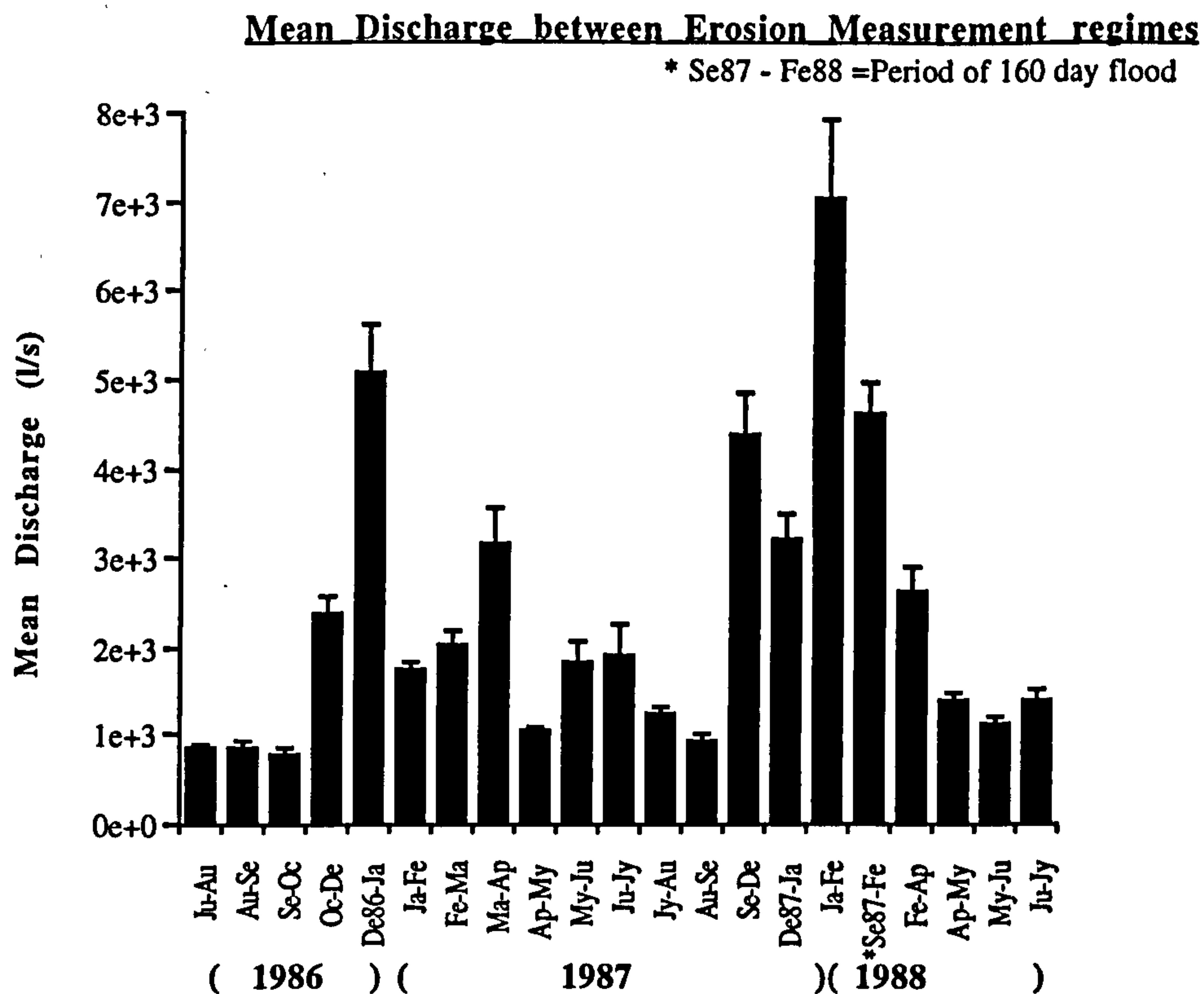


Fig.5.5 : Comparison of Erosion : Natural Vegetation Vs Natural Re-vegetation (whole banks)

Conclusions

- 1.** Even after one season of secondary succession the naturally re-vegetating banks have bare patches at the upper banks as shown in Plate 11. This is in contrast to the densely vegetated upper banks of the long established vegetation. This highlights the temporary but negative effects of advocating secondary succession as a mode of reducing bank erosion.
- 2.** By the end of the second summer (Phase 5) the naturally re-vegetated banks are well vegetated to offer similar foliage cover to the long established naturally vegetated banks. This is reflected in lowering of erosion levels to similar levels between the two treatments.

Applicability:

The above clearly shows that natural re-vegetation of a denuded bank is efficient over as short a period of time as two years (two seasons of growth) in the temperate countries. A comparable tropical country such as Sri Lanka or Bangladesh with no seasonality in growth of the native species (evergreen) will probably be as efficient in a shorter period of time. However, the clear proviso is that hydraulics of the channel will have to be adjusted during flooding seasons (normally Monsoons). In the case of irrigation channels the flow will have to be artificially controlled to allow the establishment and proliferation of the process of secondary succession of vegetation on the banks.

5.4.2f Comparison of erosion Naturally vegetated banks with newly re-vegetating banks (upper banks) (Fig 5.6)

a) Phases 1 and 2 Upper bank erosion under long established natural vegetation is almost non-existent during the period of ambient flow. On the contrary upper banks (newly denuded) allocated for natural re-vegetation (= secondary succession) increased in erosion rates. The comments and conclusions made in 5.4.2e above apply well to the process of erosion of the upper banks for Phases 1 and 2.

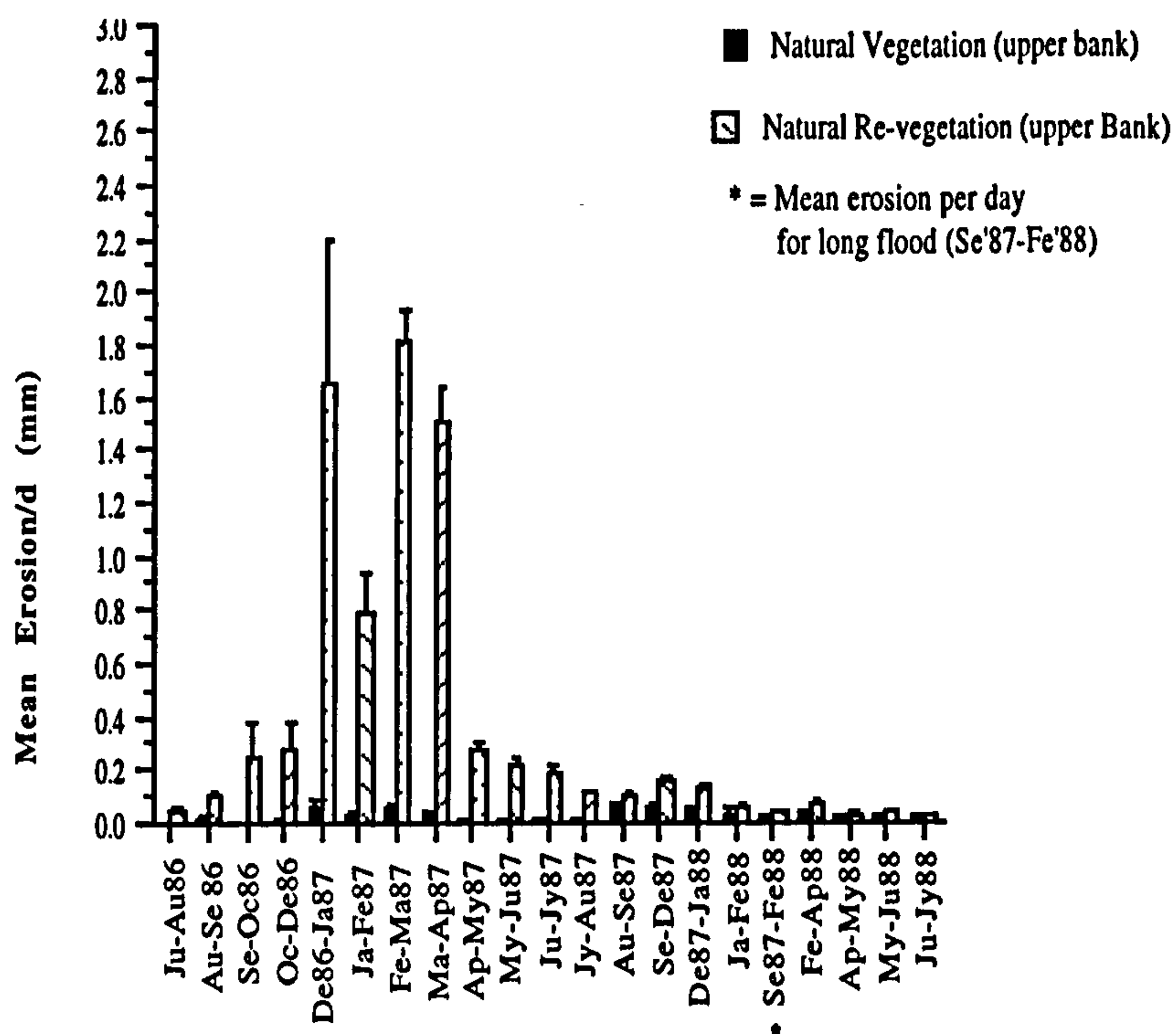
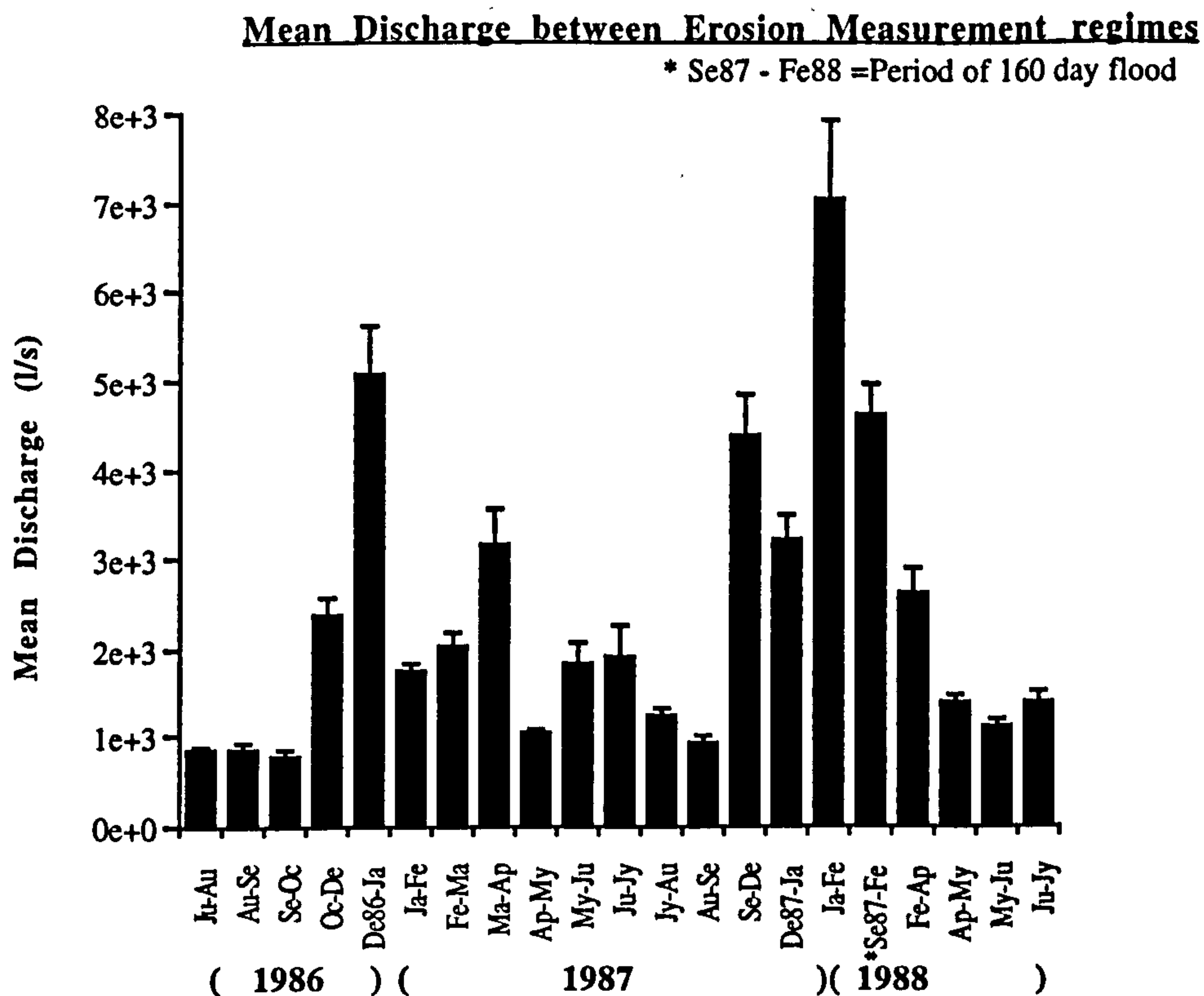


Fig.5.6 : Comparison of Erosion : Natural Vegetation Vs. Natural Re-vegetation; (upper banks)

c) Phase 3 first summer erosion within treatments(April to October 1987);

As discussed in 5.4.2e the summer reduction in erosion is almost totally due to upper bank re-vegetation. For the long established natural vegetation the minute erosion rates demonstrate the long term possibilities of a naturally re-vegetated bank after full vegetative cover for a Summer such as shown in Phase 3. The comparisons on the differential erosion rates for the two treatments are : between February to March 1987 the upper banks of the naturally re-vegetating banks were approximately 18 times (1800 %) more erodible than the long established natural vegetation areas of the bank. But by May 1987 the differential rate was only 6 times. In effect, the spring growth of seedlings should account for a two third reduction from the maximum rate of erosion observed only two months previously in the last flood of winter.

d) Phase 4 Erosion rates of the newly re-vegetating banks, after a summer of growth, show a steady reduction (see Fig. 5.6). This is due to the establishment of pioneer species under a continuously changing hydrograph . This may at face value contradict the conclusion on the necessity for control of high flows during the period of establishment of the natural re-vegetation as depicted in 5.4 above. However, it has to be made clear that the erodibility of newly colonising vegetation from the upper banks is subject to the intensity of flow and the duration of flow, both of which were much less in Phase 3 (summer) than in Phase 4 (winter).

e) Phase 5 the upper banks were generally well re-vegetated by the end of the second summer. However closer examination of some plots showed there was sparse initial establishment on the drier uppermost levels (Level 3 - 4 ; see Plate 11). But on mean erosion rates both treatments show almost similar magnitudes of erodibility.

Conclusion

Upper bank erosion in naturally re-vegetating banks is continued from winter into the following summer. During the intermediate phase the process of re-vegetation continues. The erosion rates for both treatments are similar during the ensuing winter. There is no technique to observe whether the bare (unvegetated) patches of re-vegetating plots are covered by surrounding skeletal vegetation of winter. Such orientation assisted by fluvial forces of floods is common in vegetated plots during winter flow as shown in Plates 14

and 15. Therefore a definitive conclusion on the reason for this apparent similarity of erosion rates between semi-vegetated plots and long-established vegetation is not possible.

5.4.2g Comparison of erosion of Natural vegetation versus newly re-vegetating banks (Lower banks) (Fig. 5.7)

a) Phase 1 The lack of erosion in this period for the two treatments are possibly due to two reasons. While the erosion rates for the long-established vegetation is correct, there is the element of 'experimental error' that can be brought about by debris fall from above (eroding upper banks) that accumulates covering the pin (see 2.3.6d and Fig. 2.9). Such pin readings were read as zero erosion because this study quantifies erosion and not accretion/deposition. This is fundamentally a common fault met with by all other authors who used this technique.

b) Phase 2 The onset of the first winter floods indicates an increasing erosion rate for the re-vegetating lower banks, climaxing in February to March 1987. The fact is that February to March is not associated with a high mean flow rate as much as December 1986 to January 1987. Furthermore, the erosion rate for December 1986 to January 1987 is lower than the naturally vegetated plots. The explanation is that while the December 1986 to January 1987 flood caused more lower bank erosion, it was not possible to note exactly how much it eroded because the pin tips (in some instances as discussed in Phase 1 above) were covered with the accumulated debris from above. The result is that the first flood eroded the accumulated debris first and then the lower bank top-soil which was the true zero position exposed at the commencement of the experiment. Subsequent to this, even at comparatively lower mean flow rates the exposed lower bank continued to erode. Hence we see the higher erosion rate for February to March 1987.

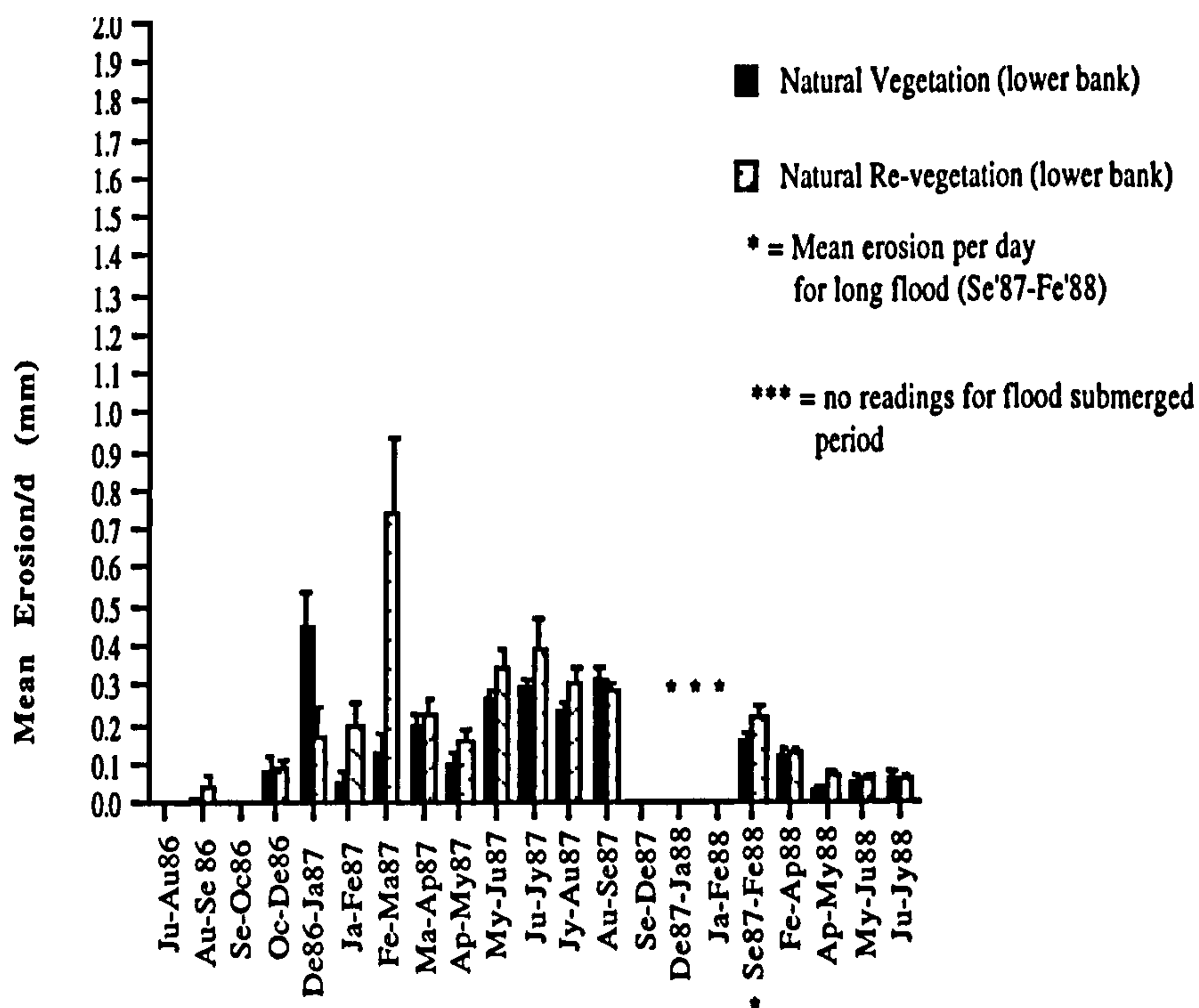
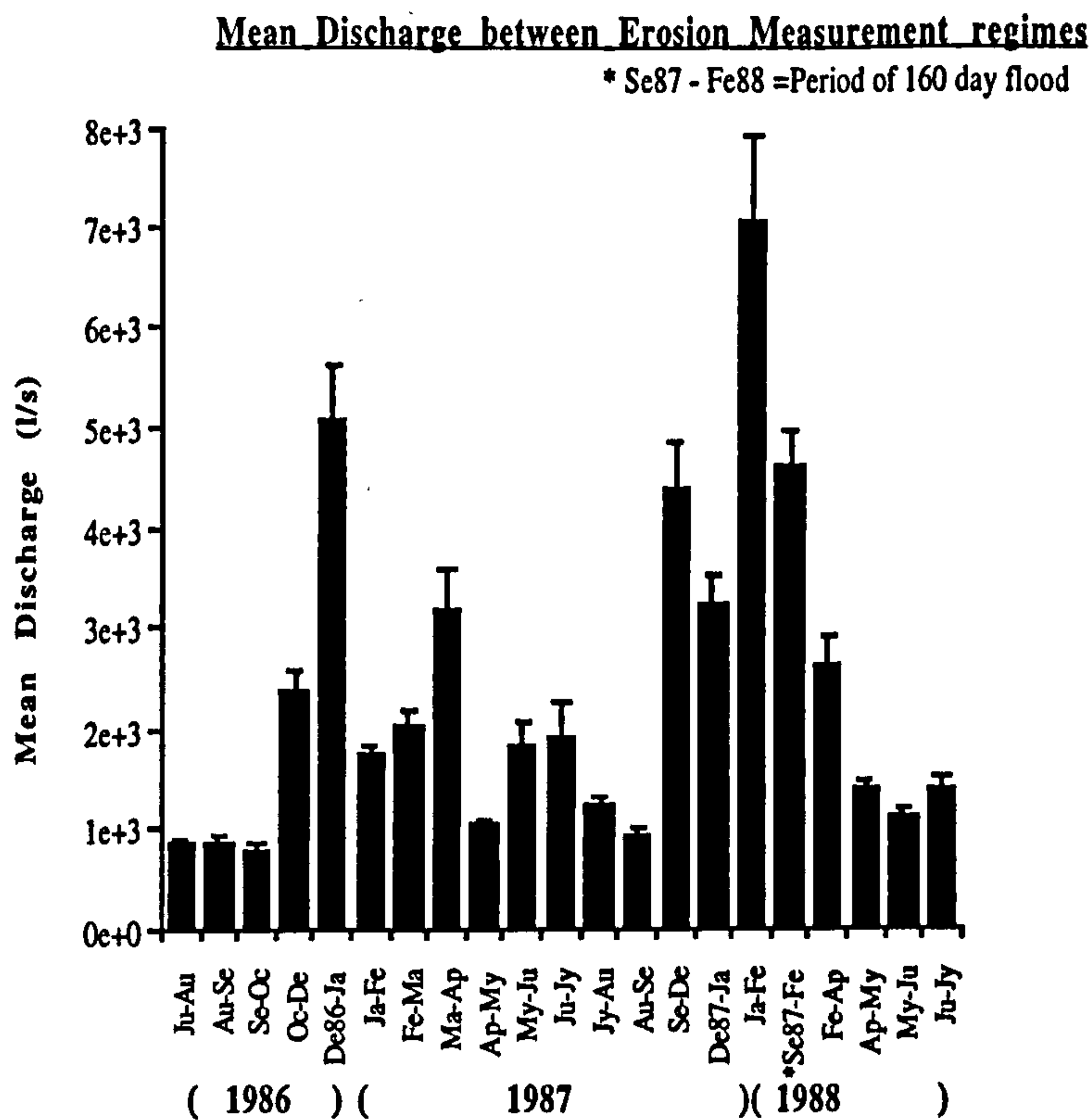


Fig.5.7 : Comparison of Erosion: Natural Vegetation Vs. Natural re-vegetation; (lower banks)

c) Phase 3 The fluctuations of the river flow levels during this Summer Phase are associated with noticeable erosion rates under both treatments. However, there is no indication that the long-established naturally vegetated banks negate erodibility of the lower banks more than the newly vegetating banks. The long-term implications are those of possible undercutting leading to upper bank instability and the need to artificially introduce or establish fringe vegetation at this level during low flow regimes so as to negate the process of undercutting.

As seen in the data of Appendices 7a, 7b and 7c, and the results of erosion readings, the reduction in erosion rates under newly emergent toe-region vegetation is attributed to the physical ground cover offered by the newly emergent vegetation. This phenomenon of pioneer colonisers reducing lower bank erosion by their presence as the physical intermediary is depicted in the proposed model in 1.2.3. In addition, these species would influence lower bank stability by their adaptive architecture (for instance, the large ground cover offered by the first leaves of many pioneer coloniser species) or even consolidation of the bank by root proliferation. However, the ecological process of competition and the subsequent process of colonisation of the mid-bank by competitors such as *U. dioica* and *E. hirsutum* may displace these species. It may not be one of direct competitive exclusion for space. But as these subsequent colonisers establish themselves the shade created by their foliage may 'indirectly' cause the toe-region pioneer colonisers to be competed out. The evidence for such an argument is commonly seen along long-established, naturally vegetated river banks as discussed earlier in this thesis.

d) Phase 4 In the absence of readings at this level for the long flood period, the analysis has to be based on the mean erosion rates per day calculated from the cumulative readings for the 160 day period. There is a higher rate of erosion for the newly re-vegetating banks when compared with the long established naturally vegetated banks. However, the fact of applicable interest is that a newly re-vegetating bank has the potential to withstand lower bank erosion almost as well as long established natural vegetation when subjected to a critical test of long and continuous flood regime.

e) Phase 5 (April to August 1988) second summer erosion within treatments :

There is a higher erosion of the lower banks for both treatments at the beginning of the summer consequent to the long flood incidence than that in the previous summer (i.e. Phase 1). This is attributed to the instability caused by the long flood incidence between October 1987 to February 1988).

Conclusion

The main conclusion from this comparison is the significance of the newly emergent toe-coloniser species which reduce erosion of the lower banks during the low flow regimes of spring and summer.

5.4.2h Comparison of erosion of a cultivated grass (*P. arundinacea*) with Naturally re-vegetated banks (whole banks) (Fig.5.8)

a) Phase 1 There are clear differences between the rates of erosion for the two treatments during this Phase (see Fig. 5.8).

The high initial rates of erosion (June to October 1986) for the *P. arundinacea* designated plots are due to the removal of some of the dead vegetation on top of the banks so as to facilitate the easy and uniform dispersal of the *P. arundinacea* seeds on the banks. This process reduced the amount of total dead vegetation in addition to causing increased destability of the top soil in certain instances by picking dead plants from the soil and the continuous removal of newly colonising seedlings of natural vegetation from these plots. In the naturally re-vegetating plots there was no such disturbance caused as they were left intact with all their dead vegetation covering the banks at all times (see Plate 9). What is noticeable is that both treatments had reached similar levels of erodibility by December 1986 even though in the previous months the two treatments had varied erosive patterns (i.e. one is associated with heavy erosion within 3 to 4 months of defoliation followed by a steady decrease in the rates over the following 3 months while the other had a continously ascending gradual increase in erosion over the 7 months.

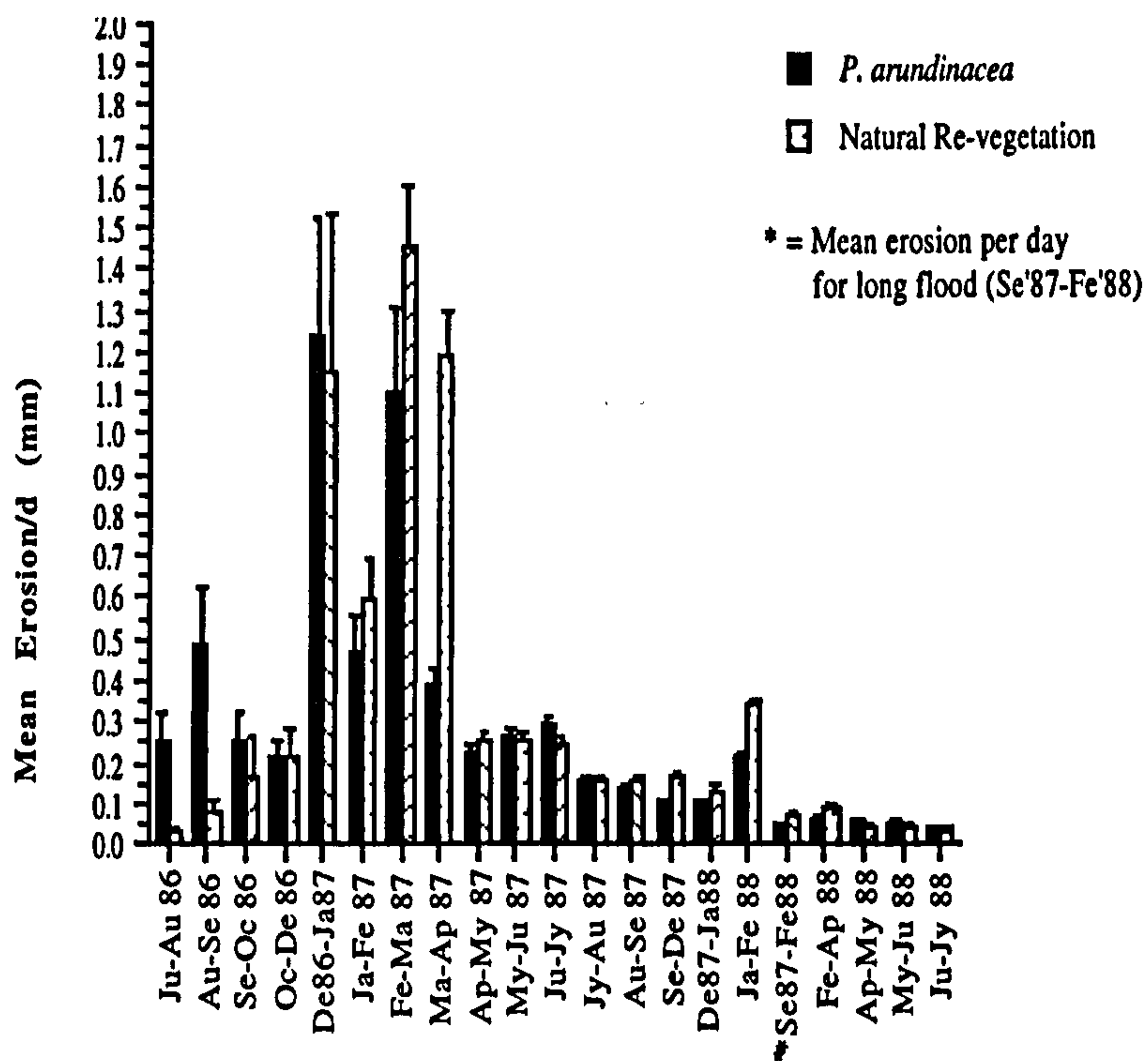
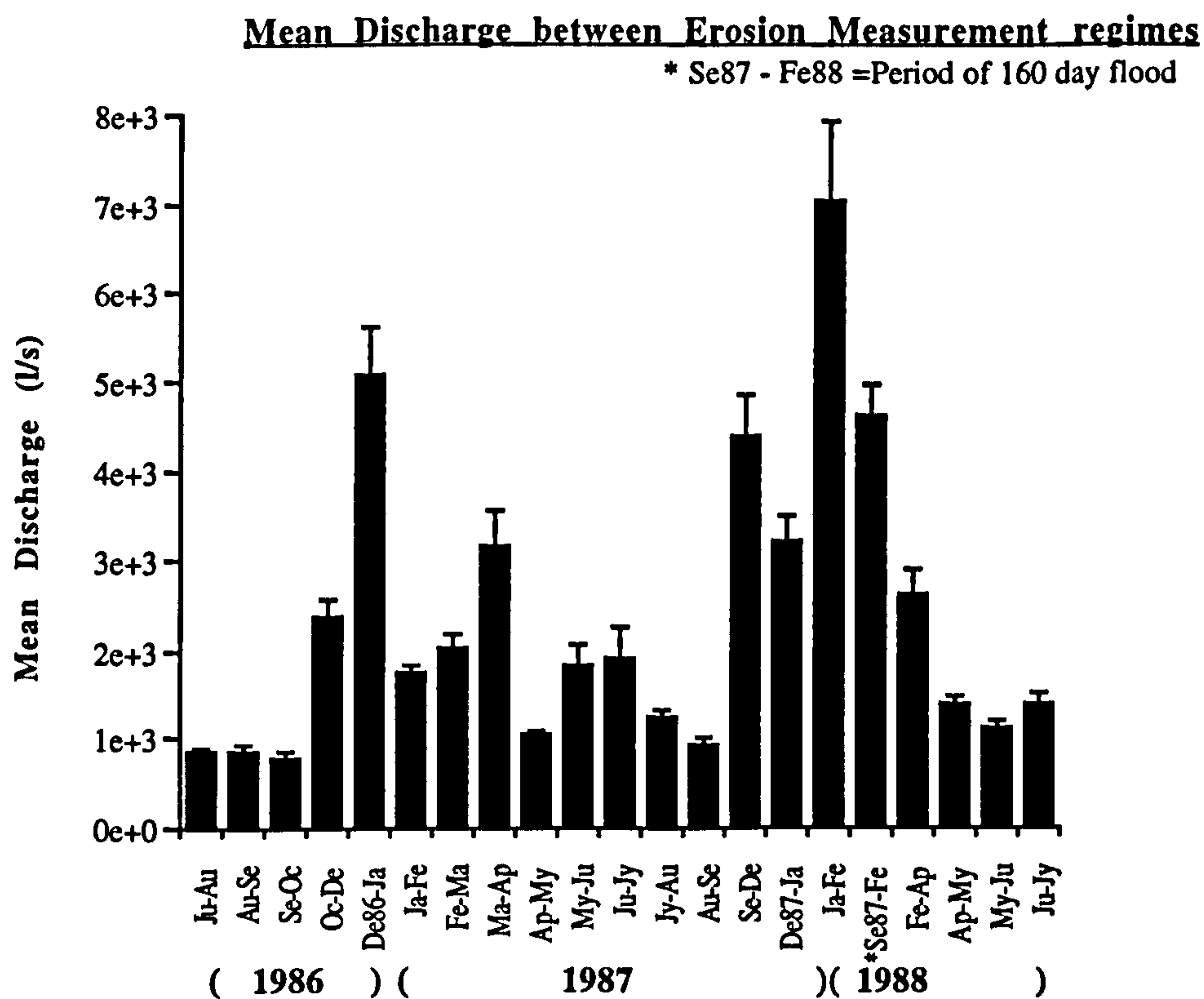


Fig. 5.8 : Comparison of Erosion : P.arundinacea Vs. Natural Re-vegetation (whole banks)

b) Phase 2 In the first flood of December 1986 to January 1987 both treatments attained very similar rates of erosion. It indicates that the top soil erosion as a result of denudation by the application of a systemic herbicide is limited to an average value if the dead vegetation is left on the banks.

During the first winter the erosion rates are very similar for both treatments for the same changes in the fluvial conditions except for March to April 1987. The much higher rates of erosion on the *P. arundinacea* seeded plots is due to the higher upper bank erosion (see Fig. 5.9) of this treatment. The cause of this incidence is probably higher wet-bank slumping in the absence of much *P. arundinacea* seedling or plant establishment.

c) Phase 3 This period of establishment of plants in both treatments is associated with almost similar but, noticeable rates of erosion during a summer of fluctuating flow levels. The most important fact is that the expected better performance from *P. arundinacea* did not occur. As such the conclusion is that both treatments are equally effective at this stage in preventing bank erosion. The lack of performance is attributed to the observed leaf forms that offer ground cover.

d) Phase 4 This critical phase is associated with a better performance in reduction of erosion by *P. arundinacea* when compared with natural re-vegetation. It is attributed mainly to better soil stability brought about by the root system and the effects of dead litter present in *P. arundinacea* plots. The leaf orientation of *P. arundinacea* is more vertical and the leaves linear when compared with the majority of the naturally re-vegetating species. As surficial soil erosion (corrasion) should be lesser with the latter species due to the higher Leaf Area Ratio changing flow levels. Minor slumping, though infrequent, was observed on the naturally re-vegetating banks as opposed to no such phenomena on the *P. arundinacea* cultivated banks.

e) Phase 5 By the second summer both treatments are very similar in their protection against erosion. By May 1988 the naturally re-vegetated banks reduce erosion equally well as the *P. arundinacea* vegetated banks. Early spring colonisers such as *Cirsium vulgare* (Spear Thistle) and *Taraxacum officinale* (Dandelion) had a prostrate leaf

orientation. This type of ground cover possibly provides better protection for the soil surface than *P. arundinacea* (which has filiform leaves), thereby preventing surficial soil erosion of banks during Summer precipitation.

Conclusion

The most significant factor is that *P. arundinacea* as a cultivated grass on the banks offers better protection from erosion up to the first summer (July 1987). Subsequent erosion of whole banks offers no such extensive differences.

5.4.2i Comparison of erosion under a cultivated grass (*P.arundinacea*) with Naturally re-vegetated banks (upper banks) (Fig.5.9)

a) Phases 1 and 2 The discussion and conclusions for the whole banks as in 5.4.2h are applicable to the upper banks.

c) Phase 3 first summer erosion within treatments (April to October 1987)

The spring of 1987 indicates the first drastic drop in the erosion rate of re-vegetation plots. The March to April erosion rate is around 1.5mm d^{-1} , while the April to May rate reduces to 0.5mm d^{-1} . This is a reduction in intensity of 67% approximately. Overall comments and conclusions are the same as for 5.4.2h.

d) Phase 4 and 5 the results of erosion rates for upper banks are very similar to those of whole banks; As such the discussion and conclusions in 5.4.2h apply equally well to these results.

Conclusions:

Upper bank colonisation by natural re-vegetation is a slow process when compared with artificial establishment of a wetland grass such as *P. arundinacea* (at similar levels on the bank). This is reflected in the higher and continuous erosion of the upper banks in the former process as opposed to the latter.

April to May of the first year of secondary succession is the critical period during which erosion of banks is arrested to a significant level. The reason for this is the new ground cover from the newly emergent pioneer colonisers.

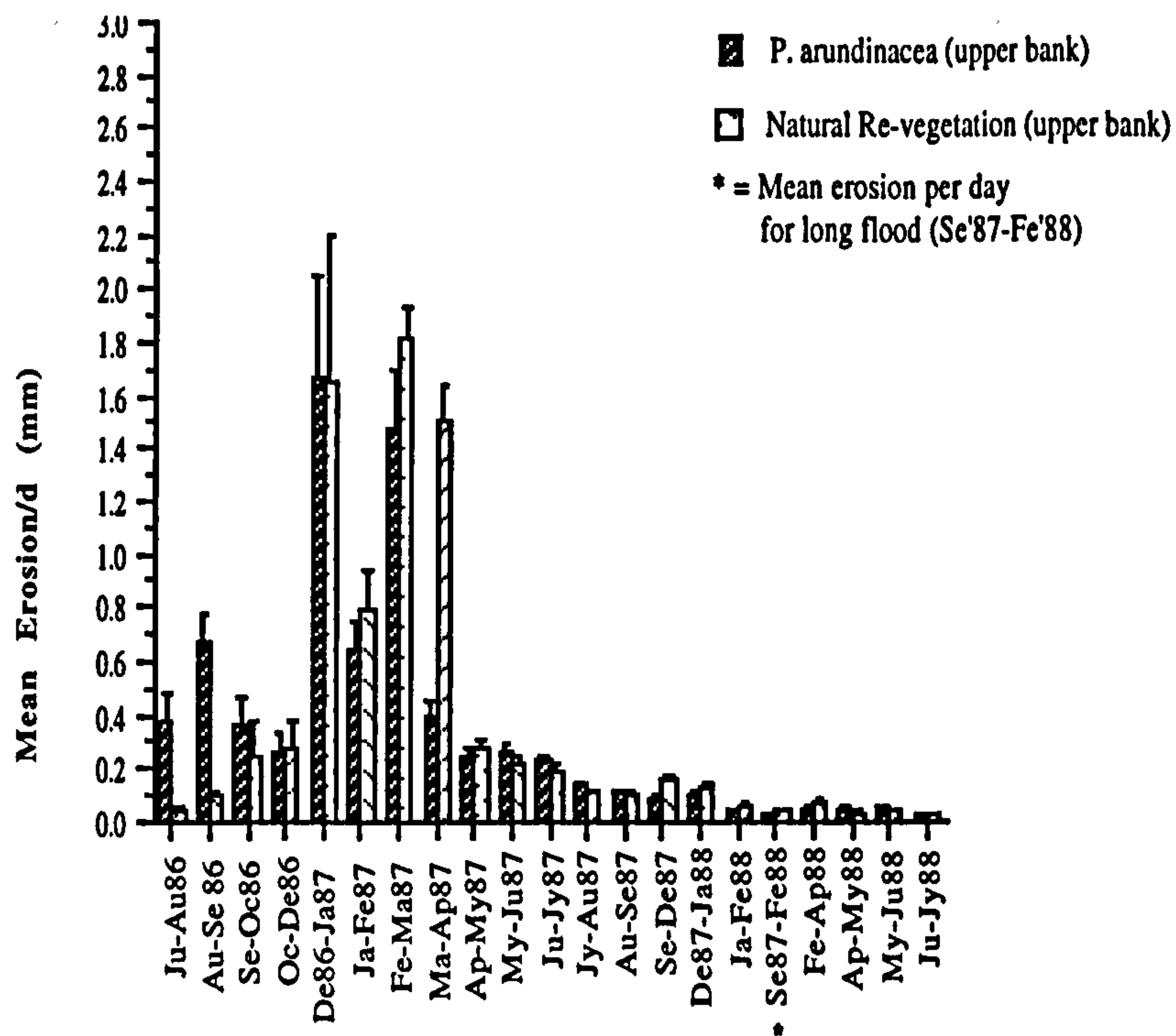
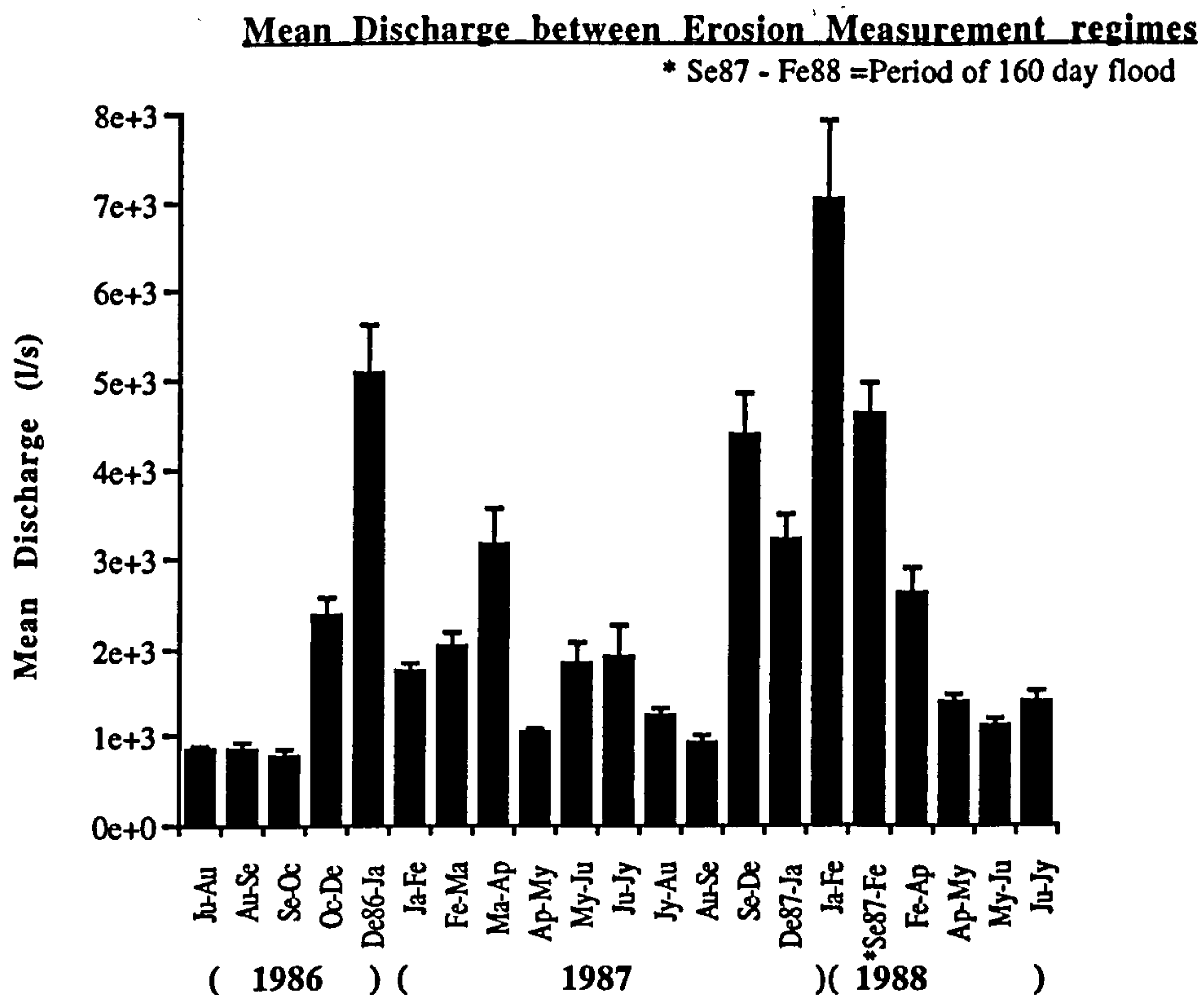


Fig.5.9 : Comparison of Erosion: *P. arundinacea* Vs. Naturally Re-vegetated banks; (upper banks)

5.4.2j Comparison of erosion under a cultivated grass (*P. arundinacea*) with Naturally re-vegetated banks (lower banks) (Fig.5.10)

a) Phase 1 (June to December 1986)

The plots allocated for *P. arundinacea*. have a relatively high rate of lower bank erosion upto December 1986. Naturally re-vegetating plots have initially lower rates of erosion (August to September 1986) but by December 1986 have reached similar levels to *P. arundinacea*. allocated plots. Variations of erosion rates are not attributed to much growth of vegetation on the *P. arundinacea* plots as opposed to that on the naturally re-vegetated plots.

b) Phase 2 On the whole there is no significant difference between *P. arundinacea*. seeded banks and naturally re-vegetated banks during this period ($F = 2.269$; $p = 0.1629$). However *P. arundinacea*. seeded banks have a higher rate of erosion ($0.4\text{mm}^{-\text{d}}$) in December 1986 to January 1987 when compared with $0.15\text{mm}^{-\text{d}}$ for the naturally re-vegetating banks. In January to February 1987 the rates of erosion are lowered for *P. arundinacea* seeded plots while the naturally re-vegetated banks maintain a steady rate of erosion. In the following period of high flow in February to March 1987, both treatments undergo higher erosion rates in the toe-region. While the naturally re-vegetating banks have erosion rates of $0.7\text{mm}^{-\text{d}}$ *P. arundinacea* seeded banks erode at $0.25\text{mm}^{-\text{d}}$. Over the next month naturally re-vegetated banks reduce the erosion rates to $0.25\text{mm}^{-\text{d}}$ while the *P. arundinacea*. seeded treatment remains almost constant.

P. arundinacea vegetated plots had an advantage in being hand sown in a regular distribution. Natural re-vegetation plots had to undergo normal secondary succession processes. Observed reduction in erosion rates in the spring of 1987 in the naturally re-vegetated plots were due to the new flush of spring growth in the toe-region. It is proposed that the spring growth of toe-region vegetation acts as:

- (a) an effective and necessary first stage in the prevention of toe erosion;
- (b) such a process will enhance the stability of the upper bank and act as a barrier for debris fall from the upper banks to the river. Hence it enhances accretion of soil in this region.

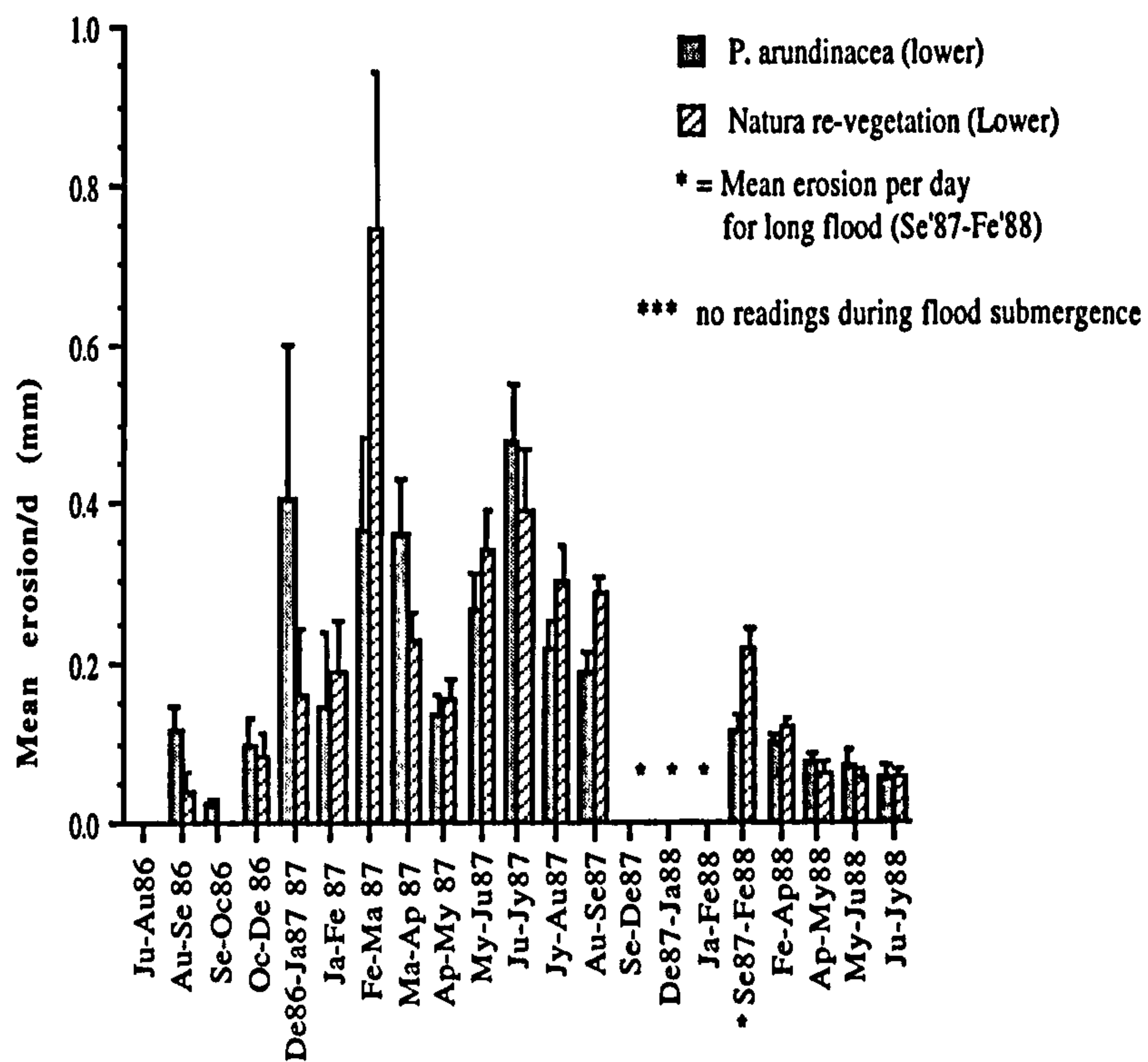
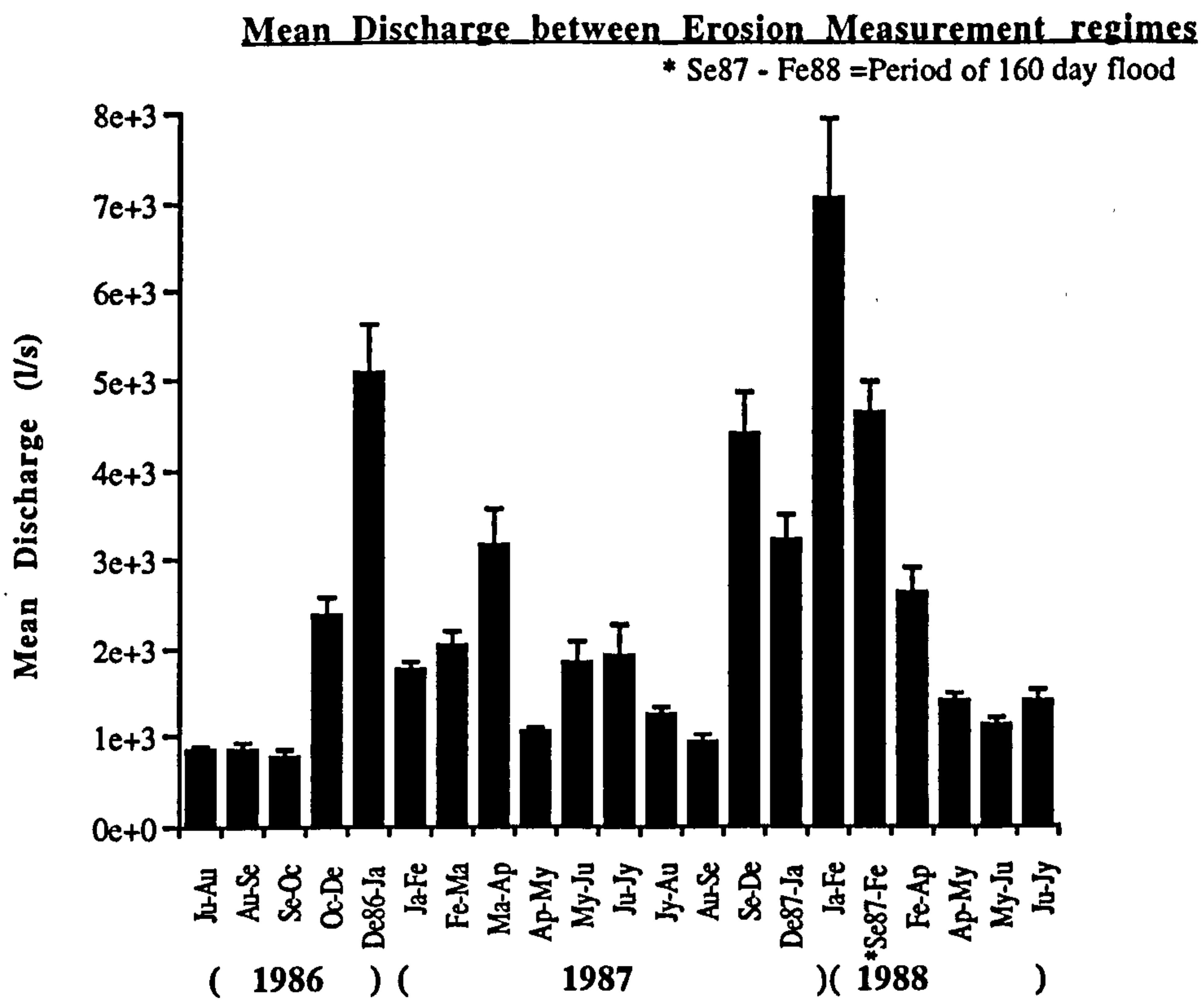


Fig. 5.10 : Comparison of erosion : *P. arundinacea* Vs, Naturally re-vegetated banks (lower banks)

c) Phase 3 (April to October 1987)

First summer erosion within treatments indicates no significant differences between the treatments. Analysis of variance yields an F value of 0.575 and a probability of 0.4659. Both treatments show higher than expected erosion rates for the lower banks during the Summer of vegetative growth. The reason is that the fluctuating river hydrograph prevents the total colonisation or seedling establishment leading to much vegetation cover in this region of the river banks.

d) Phase 4 (September 1987 to February 1988)

During this critical period there is a significant difference between the treatments. Analysis of variance indicates a probability of 0.0319 ($F = 6.433$). On the basis of relative merits in the pattern of establishment of cultivated *P. arundinacea* and natural re-vegetation the reduction in erosion at the toe-region by the former after one season of healthy establishment is better. This is shown clearly in the marked reduction in the rates of erosion over 160 days between September 1987 and February 1988 when the two treatments were subjected to the classic test of a long and continuous storm flow. *P. arundinacea* established banks have half the rate of erosion $0.1\text{mm}^{-\text{d}}$ to that of naturally re-vegetated banks $0.2\text{mm}^{-\text{d}}$. This is more due to the roots from Level 2 consolidating the bank-toe region or the dead leaf litter cover on the toe-region than the establishment of vegetation at this level (Level 1).

e) Phase 5 (March to July 1988)

Statistically there is no significant difference between the treatments ($p = 0.5095$; $F = 0.468$) for the second summer erosion (April to August 1988). Both treatments show decreased erosion rates. It has to be concluded that erosion in the bank-toe region has not been negated totally, either by artificial means (cultivation of a wetland grass) or the natural growth of vegetation.

Conclusions

P. arundinacea and natural re-vegetation act almost similarly as bank-toe protectors under the ambient and sub-bankfull flow regimes that prevailed over the experimental period. The process of wash away of *P. arundinacea* seeds and the

fluctuating summer flow levels in Phase 3 presumably prevented the establishment of vegetative (pieces of roots, rhizomes, or shoots) or sexual (seeds) propagules in the naturally re-vegetating (Experiment 3) bank-toe region.

During the critical period of prolonged floods with bankfull flow *P. arundinacea* was significantly better as a toe-protector.

5.5 Secondary succession within the first 25 months of denudation

As shown in Appendix 7a, 7b and 7c, the species that colonised the banks over this period were not the main spatial colonisers of the mid and lower banks (levels 2, 3 and 4) of the old naturally vegetated banks "climax" community. It is noted that these levels correspond to the levels of erosion measurements (Fig. 2.8b) with the positions at 2.5 metres from the bank-toe (see Fig. 5a) included as level 4 for this discussion as it was the apex of the bank slope. In fact there were hardly any plants of *U. dioica* recorded within the first two months. There were only four plants of *E. hirsutum* recorded. *P. arundinacea* did grow more as seedlings at levels 2 to 3, but not at the waterline (none of these were at the positions recorded in the Appendix).

The pattern that emerges is as follows :

Level 1 (at the waterline; positions A1 to D1 in Fig. 5a)

Colonisation is sparse in April 1987. By September 1987, wetland bank vegetation such as *Glyceria maxima*, *Ranunculus sceleratus* and *Veronica spp.* are noted; *Rumex spp.* are present. The May 1988 data show that this region is mostly colonised by *G. maxima*, *Juncus spp.*, and *Cirsium spp.* (see Plate 12 for August 1988).

Level 2 and 3 (mid-bank; positions A2 to A3 and D2 to D3 in Fig. 5a)

The absence of many species by April 1987 is well compensated by September 1987. By then, this region has more variety of wetland and dryland plants. *Rumex*, *Cirsium*, *Carduus*, are present together with *Veronica spp.* grasses such as *Poa spp.* and others such as *Lychnis flos-cuculi* and *Trifolium repens*. The May 1988 data shows that there has not been much species turnover in this region. The new species noted is *Impatiens glandulifera*.

Levels 4 and 5 (upper-most region; A4 to A5 and D4 to D5)

This region is dominated by different species of grasses from April 1987 throughout to May 1988. However the mid- region was not well colonised even by July 1988 due probably to the more unstable soil compounded by a high gradient and the dry soil (see Plate 11).

In 5.1. two fundamental questions were asked (viz. can the initial colonisers arrest erosion of a bare bank? and what species are they?). The results and discussion from 5.4.2a to 5.4.2h above indicate that negation of erosion is possible within two seasons by natural re-vegetation to a standard comparable with long-established climax bank vegetation. However, as shown in 5.5 above, it is not due to the major spatial constituents (*Epilobium hirsutum* and *U. dioica*) present in the climax community that are responsible for this. Whether the climax community constituents are capable of arresting erosion rather than prevention of it during major channel discharges is not answered in this treatise. The second question as answered in 5.5 and shown in Appendix 7a -7c, clearly shows that the first colonisers that arrest the erosive process comprise a very different range of species from the climax community. It has to be qualified by stating that the grasses that form both the initial colonisers and the climax community in the generally non-erosive apical region of the bank remain as a stable community throughout.

5.6 Summary of conclusions on the effects of natural re-vegetation of banks

- i) Dead vegetation cover on devegetated banks helps to reduce their erodibility in the first floods consequent to denudation .
- ii) Following the wash out or decay of the mulch cover the erodibility of the exposed soil increases to that of a bank which had its dead vegetation removed (bare bank) after the application of the herbicide .(see Figs. 5.1, 5.2 and 5.3).
- iii) The process of natural re-vegetation in the toe-region is almost complete within one season of growth such that the erosion rates are decreased to the same levels as a long-term naturally vegetated bank (see Fig.5.5).

- iv) Within 18 months the naturally re-vegetated plots reach the low erosion rates of naturally established mature bank vegetation (see Figs. 5.5 and 5.6).
- v) There is a marked reduction of erodibility of the soil with the initial stages of establishment of ground cover species that initially colonise a disturbed/devegetated bank slope.
- vi) With time, the phenomenon of reversal of the relative magnitudes of rates of erosion within the bank profile occurs. In essence, the upper bank which initially (eg. January, February, March 1987) showed a much higher rate of erosion when compared with the lower bank, indicates a lower rate of erosion from July 1987. The causative factor is the new flush of re-vegetation growth of the summer of 1987.
- vii) Natural re-vegetation of a devegetated bank is equally efficient for negation of erosion of banks as much as the cultivation of a wetland grass by seed propagules.
- viii) The time period for returning to normality is between one to two seasons of growth, on the proviso that there are no summer floods of magnitudes that are highly erosive.
- ix) Artificially introduced *P. arundinacea* may be a better bank-toe protector than the natural re-vegetation in terms of negation of erosion on a longer temporal basis (Compare Plates 7 and 8 with 11 and 12). This conclusion is further enhanced if we consider the fact that the toe-region of the climax community banks are bare. This phenomenon is due to the ecological aspects of competitive exclusion. The main mode of competition is shading by the highly competitive *Epilobium hirsutum* and *U. dioica* in the mid-bank. As such when the first colonisers (see 5.5) are replaced in the last stages of secondary succession by these species the toe-region would be bare and open to under-cutting. On the contrary as seen in Plate 8 and the Survey in Ch.6. the *P. arundinacea* is invasive on to the toe-region as its permanent 'niche'. With time, that species would probably be superior to the process of natural re-vegetation.

5.7 A critique of observations of Bank Processes observed within the experimental area

There were four erosive processes observed on the banks during the experimental period. They are discussed below with the observations and photographs.

i. slumping (see plate 13)

Much research, analysis and discussion have been concentrated on slumping (see 1.3.2) of banks of waterways. Upto now, the effects of post-inundation destability and erosion of banks have been discussed as a critically important bank process without much contribution on the effects of bank vegetation on this process. Previous contributions on slumping as explained for bare banks is acknowledged in 1.3.2. As applicable to this study, it is relevant to discuss the observations on slumping as a process following systemic herbicide application on a bank vegetation.

The crucial factor is the death of the whole plant, including the root system which is ramified within the bank soil matrix. This is different greatly from the normal pattern of seasonal death of foliage during winter. The latter is a normal phenomenon in temperate regions. The difference between the two forms of defoliation is that while there are live roots in the vegetated but winter defoliated bank vegetation, all roots are dead in the systemically defoliated bank vegetation. The results of root lengths per unit volume of soil over a two year period as discussed in chapters 3 and 4 confirm the above conclusions.

The main observation was that the dead root systems had limited ability in preventing the process of slumping in the denuded plots. There was extensive evidence of broken dead and brittle roots on the slumped soil as well as on the overhang left on the banks. The inference is that once any position on the bank slope was weakened by the death of the rootmesh within the soil matrix, the gravitational forces were responsible for the slumping of the soil. This was most severe in the periods following inundation.

ii patchy erosion (see plates 11 & 14)

For the long-established naturally vegetated plots, there were two forms of patchy erosion observed. As seen in Plate 14 and discussed in Table 7, they are prevelant when:

(a) the bank is sparse in vegetation at the toe-region; or

(b) existing vegetation such as *U. dioica* and *E. hirsutum* that were overhanging onto the waterway either as healthy shoots during summer or dead defoliated skeletal foliage in early winter, may be physically oriented upwards on the bank. This process of physical

orientation of the bank cover is a result of the motive force of flood water. The result is exposure of the lower bank to patchy erosion; this is clearly seen in plate 14.

In summary, the main reason for this type of erosion is the absence of either a layer of live vegetation (during summer stormflows) or a skeletal but anchored dead vegetation forming a 'protective soil-matting' during winter stormflows.

In the artificially denuded banks which were allowed to naturally re-vegetate, patchy erosion was observed mainly in the first winter (1986/87) and to a lesser extent in the second winterflow (1987/88). The reason was the already bare patches of bank which were not colonised by any vegetation as seen in plate 11. Even though this study did not attempt to address the ecologically important concepts of species establishment in hollows and hummocks, what we clearly observe in this study is the geomorphologically significant formations of hollows and hummocks as a result of denudation and associated hydrographic changes along the banks. The results as discussed in 5.4.2e, 5.4.2f and 5.6, demonstrate that patchy erosion is a temporary process lasting the first growing season or at most the second. A future study on species establishment on hollows and hummocks of an eroded bank is suggested.

More significantly, there is an applicable interest for the tropical waterways that have controlled flow, to ensure that patchy erosion should be remedied on a basis of regular maintenance of the banks. Failure may result in serious bank erosion. The alternative is to repair such positions by submergence-tolerant species of vegetation that are also fast colonisers. Future research projects will have to address this aspect in terms of species suitability for the particular bank soil, geographic location and climatic variations among a host of factors relevant to the location.

iii. secondary flow affecting the upper bank

Thorne (1978) and Thorne and Tovey (1981) have highlighted the secondary flow effects on bank erosion. In this study, it has not been the intention to address this process in detail. The reasons were : (a) the vast diversity in magnitudes of secondary currents that may be associated not only with varying hydraulic regimes but also arising out of the morphological diversity of the bank vegetation protruding into the channel from the banks; (b) the limitations of relevant equipment for quantification of secondary current

measurements; and (c) the time allocation and the technical assistance necessary for such operations.

However, one significant observation after stormflows was the existence of increased erosion in the centre of the exposed bare banks. It is suggested that following the slump erosion in the first winter (1986/87), there was the formation of a whirlpool effect in the second winter floods. Such a whirlpool-effect is brought about by the isolation of an eroded (concave) bank between the vegetated, planar or slightly convex lateral boundaries.

iv. undercutting (see plates 5 & 15)

The process of undercutting of banks within this experimental area has been mentioned in 1.3.1 and discussed in 3.4.2b and 3.4.2e. What the discussion highlighted was the extremely minimal but consistent undercutting during ambient flow periods (summer) in the unvegetated toe-region of the river. The significant aspect is the observation of 'pockets' of undercutting during winter flooding (see plate 15) in the toe-region of naturally vegetated plots. This phenomenon can be attributed to two causes. The first is the induction of minor but erosively significant secondary current formation due to the obstruction of the main flow by overhanging debris which is clearly evident in the plate. The second causative factor is the absence of any dead vegetation that is anchored onto this toe-region in contrast to the anchored dead vegetation just above. This has a destabilising effect. The short term result is the process of undercutting. The long-term effect may be the process of 'pseudo cyclic slumping' (Knighton, 1984) which has grave implications for the erodibility of the bank *en masse*.

Chapter 6

A Survey of variations of shear strength, moisture content and root density in banks under long-term established monoculture stands

6.1. Introduction

Attempts to establish species of plants on river banks to prevent erosion may present some short-term as well as long-term problems. For instance, on a waterway which has a low regular flow as in most rivers and irrigation canals, the success or failure of establishment following the introduction of a species of plants on a bank depends upon many limiting factors of a biotic and abiotic nature. Of those limiting factors one of the most critical is water. The moisture gradient on the bank profile as well as the flow characteristics of the waterway delineate the long term 'niche' (Hutchinson, 1957) of the species.

Research and advisory work carried out on the establishment of monocultures of different species of plants (Cox,1942; Ree,1949; Gardner and Freyburger,1949; Eastgate,1969) for prevention of bank erosion appears to presume that once introduced the plants will grow at the same densities both in number of plants per unit area of soil and the total root length per unit volume of soil. But this may not hold true with time as limiting factors such as variations of moisture content up the bank will determine the preferred long-term micro-habitat (realised niche) of the given species. A complex range of factors that will determine the short-term as well as the long-term establishment of a given species of plants have been discussed in 1.4.4.

Civil engineers, having identified the necessity for the use of vegetation on banks to prevent erosion, appear to oversimplify the complexities of plant diversity in nature. The result would be either impractical proposals or expensive maintenance problems in applied practice. Nature on the contrary, has evolved eco-systems with dynamic parameters such as different species of plant growth on banks of rivers which lend long-term stability to river systems such as those discussed by Smith (1976) Ideally, one must learn from nature.

The attempt herewith has been to identify some naturally occurring bank species of vegetation that have over a long term established themselves for more than a decade, in their preferred micro-habitat along the bank.

The habitat preferences of the species chosen for this survey have been confirmed by other authors (see Fig.6.1; Haslam,1978)

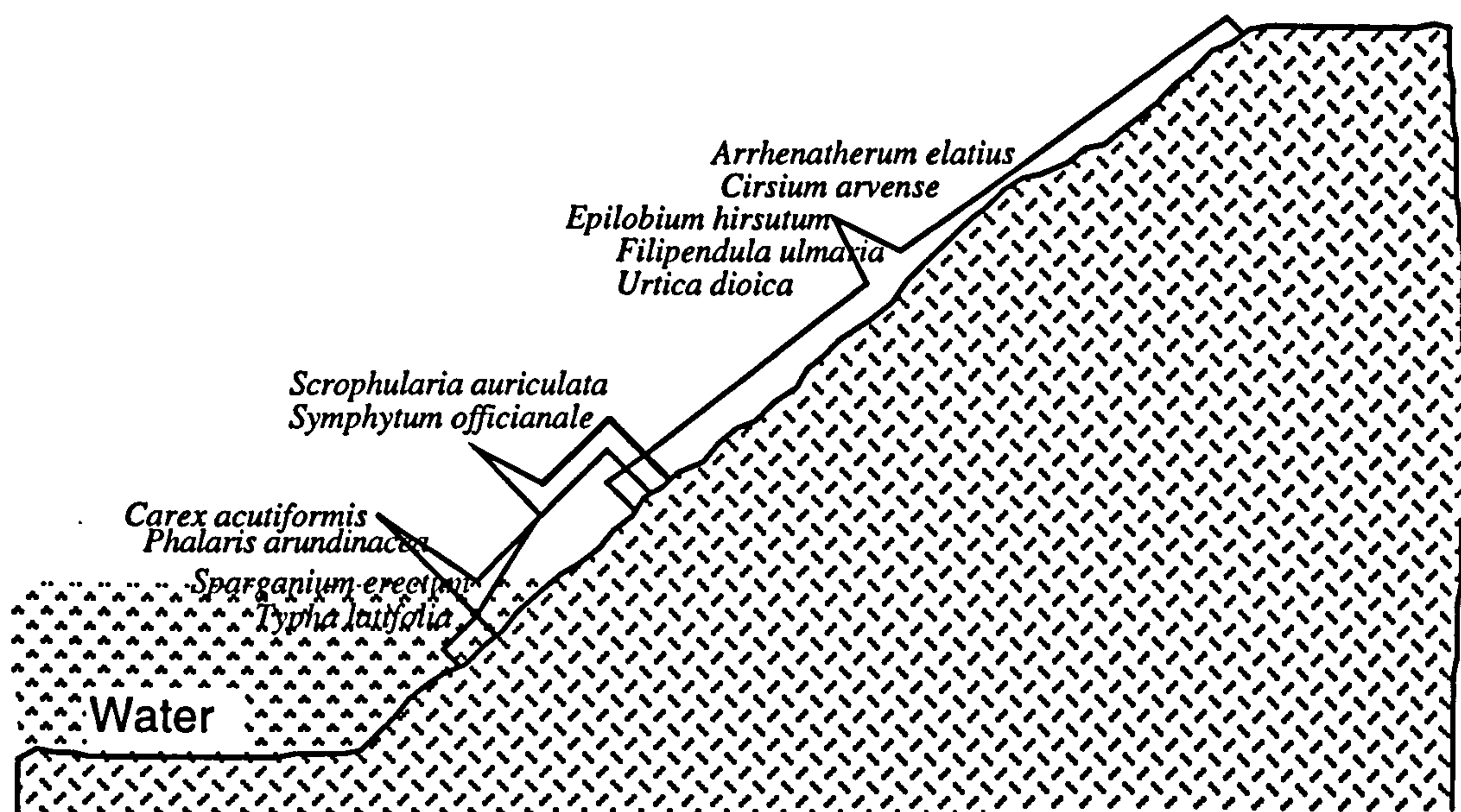


Fig. 6.1 : The habitat preferences of certain groups of herbs and grasses of bank plants in relation to water level (after, Haslam,1978)

The three species of plants chosen for this survey are depicted above. They are : *Phalaris arundinacea* as representative of the semi-aquatic habitat ; *Urtica dioica* and *Epilobium hirsutum* are representatives of the mid to upper bank region ;

The above habitat preferences were evident in the field not only around the River Ouzel but throughout my observations around England and Wales. *Phalaris arundinacea* was notable in its preference to establish itself at the periphery of lakes and the basal end (toe-region) of waterways. Throughout the experiment on artificial establishment of *P. arundinacea* (Ch. 4) it was evident that initial establishment of seedlings was better in the upper region (upwards of 0.75m the base of the bank). But the apparent vigour of growth of the plants and the rate of vegetative reproduction in the second season of growth was more obvious in the lower region (0 to 1.0 m from the base of the bank). It was also noted that initial seed germination and seedling establishment in the 0 to 0.75m basal

region was remarkably low. This may have been due to wash off of the seeds in this region by temporary rise in water level. Such a factor can have positive effects for the dispersal of seeds downstream. On the other hand, even though these seeds are initially washed away, the plants that have established themselves in the mid-band region of the bank appeared to compensate for this loss by rapid vegetative colonisation towards the base of the bank. This would logically ensure the presence of the much needed 'buffer zone' of vegetation between the motive force of the water and the potentially erodible bank soil. Such a phenomenon may be of possible geomorphological significance with regard to the stability of the bank profile and the long-term morphology of the channel. Would such establishment of vegetation ensure that no points of weakness along the bank arise at any time thereby negating any points of initiation of erosion that may develop into permanent channel morphological changes ? If the different species of plants depict model characteristics with reference to conservation of banks then one could argue that while the concept of evolution and niche of plants in different habitats has been proven, there remains an arena for the argument as to whether the evolution of river systems (Davis,1889) had a significant association with the presence or absence of certain 'bank binding' species of plants.

For the present investigation more fundamental questions are raised as the aims of this survey. These questions should precede any possible scientific hypothesis that may be formulated in response to the above complex set of possibilities of geomorphological significance.

6.2 Aims of the survey

Three species of commonly occurring river bank vegetation of Buckinghamshire were chosen as representatives of the two distinct regions of the banks (lower and upper). They are described in 6.3. below.

They were most relevant as all three species were in the experimental regime also.

This study addressed the following questions :

- i. Are there significant differences of the shear strength of the bank soil among the three species of vegetation surveyed as monocultures of natural bank colonisers ?**

- ii. Are there any significant differences in the total root length per unit volume of soil of the three species of vegetation surveyed ?
- iii. Are there any significant differences in root density between species that grow at similar heights on the bank profile ?
- iv. Is the variation of root density, if it exists, co-related with a variation of shear strength of the soil ?
- v. Do different species of plants have different influences on the moisture content of the bank soil ? For example, both *Urtica dioica* and *Epilobium hirsutum* co-habit at the same height of the bank, but are there any significant differences in moisture content ?
- vi. For a long-established monoculture on a river bank, is there a variation of root density upwards along the bank (i.e. is there a significant variation of total root length per unit volume of soil)?
- vii. Is there a relationship between shear strength of the soil, the total live root length present per unit volume of soil and the percentage moisture content in the soil in which the three species of vegetation grew ?

6.3 Materials

6.3.1 Species chosen

From the various species of bank vegetation observed on both banks of the river, three species of bank vegetation were chosen for the survey. They were:

- a) *Phalaris arundinacea* L. (Reed Canary Grass)
- b) *Epilobium hirsutum* L. (Great Hairy Willow Herb)
- c) *Urtica dioica* (Stinging Nettle)

They represented the following basic criteria that were considered to be essential for the study:

- i) comparatively large areas of long-established monocultures of the species be present on the bank. This would reduce the experimental errors that can be brought about by surveying in areas of mixed species.
- ii) at least three similar replicates of the survey plots be available within a kilometre of the bank length. This would reduce the variations of soil structure, composition and hydrological factors the selected plots of plant species have been subjected to over their

long period of establishment. It would be reasonable to presume that variations in the magnitude of the three parameters measured within replicates could be expected if the surveyed samples originated in sites of significant varying soil and hydrological parameters. This survey is a seminal study on relationships between three associated parameters of soil vegetation systems. As such, simplistic fundamental models are expected on which further research may be developed for variations in habitat characteristics.

iii) the habitat preferences of the species of plants chosen must have some relevance to their possible role in relation to bank erosion. The species should be long-term colonisers of the bank with preferential habitat demarcations (eg. toe-region coloniser as opposed to mid-upper bank colonisers). The physical and chemical composition of the soil would delineate the establishment and survival of the species. Much of the guide lines to the above criteria are elaborated for each species by Grime et al (1986).

6.3.2 Site Description

The reason for the choice of monoculture sites in the vicinity of the experimental area were described in 6.2. above.

Phalaris arundinacea site 1 was a well established patch of plants of approximately 3m wide and 0.8 to 1.0m up from the base of the river. The plants were densely packed with the lower region at the water level but not invasive into the river for more than 40cm (approximately) from the toe of the bank soil. A dense root and rhizome mattress was evident at the bottom region. Above this 1.0m level were a mixture of grasses and *Urtica dioica*. This site was approximately 25m down river (from plots 1a & 1b) from the experimental site.

P.arundinacea site 2. was another well established patch of plants approximately 20m from the opposite end (plots 15a & 15b) of the river upstream. This patch of plants was approximately 2.5m wide and 0 to 1.0m upwards from the base of the bank. It was similar to site 1 in almost all apparent morphological characteristics.

P.arundinacea site 3. was located a further 25m approximately upstream from site 2. It was measured to be in excess of 4m in width and extended 1.5m upwards the bank

from the toe of the bank. The upper bank vegetation beyond the 1.5m was mainly composed of grasses.

***Urtica dioica* site 1** This was a mature patch of nettle monoculture with late season flowers. The location was approximately 100m upstream from plots 1a and 1b of the experimental site. The clump of plants was approximately 4m wide. It occupied a habitat above 0.4 metres from the water level (ambient flow). From this 0.4m margin it proliferated upwards approximately 1.8m towards the top of the bank.

***Urtica dioica* site 2** was situated a further 50m upstream from site 1. The plants were in much the same condition as in site 1. But the bank profile was notably one of mid-bank subsidence to a flat topography.

***Urtica dioica* site 3** was on the opposite side of the river to site 2 with very similar plant density and maturity as in sites 1 and 2. The bank profile was one of angular uniformity as representative of 1:1.5 bank slope.

***Epilobium hirsutum* site 1** was adjacent to site 2 of *U.dioica*.. It had mature stemmed plants with a noticeable density of flowers and seed plumes.

***Epilobium hirsutum* site 2** was approximately 100m upstream from site 1. It had very similar characteristics to site 1 in both physiographic features and plant density and demography.

***Epilobium hirsutum* site 3** was on the opposite bank to site 2. with very similar features of the bank and the plants. The uppermost region all the banks were dominated by grasses (mainly, *Agrostis stolonifera* , *Agrostis gigantea*., *Poa* spp. and *Festuca* spp.).

6.3.3 Dates of the survey

The field work was carried out between 10th and 15th of September 1987. In keeping with observations of others such as Ranwell (1961) and Hussey and Long (1982) August to September is associated with the highest root biomass in general. These refer to saltmarshes. No special literature was available for rooting habits of river bank plants. The laboratory work on root counts was carried out within the week and completed by 19.9.87.

6.3.4 Equipment used and the procedure adopted for measurement of shear strength, soil moisture content and total root length per unit volume of soil were the same as those used in the series of experiments in Chs.3, 4 and 5.

6.3.5 Sampling Procedure

a) Shear Strength measurements

For all three species the sampling points were as shown in the grid pattern in Figure 6.2 below.

Shear strength measurements were made at depths of 10cm from the apparent surface of the soil. The accuracy was limited to 1-2cm above the true 10cm depth as the dense vegetation prevented perfect accuracy.

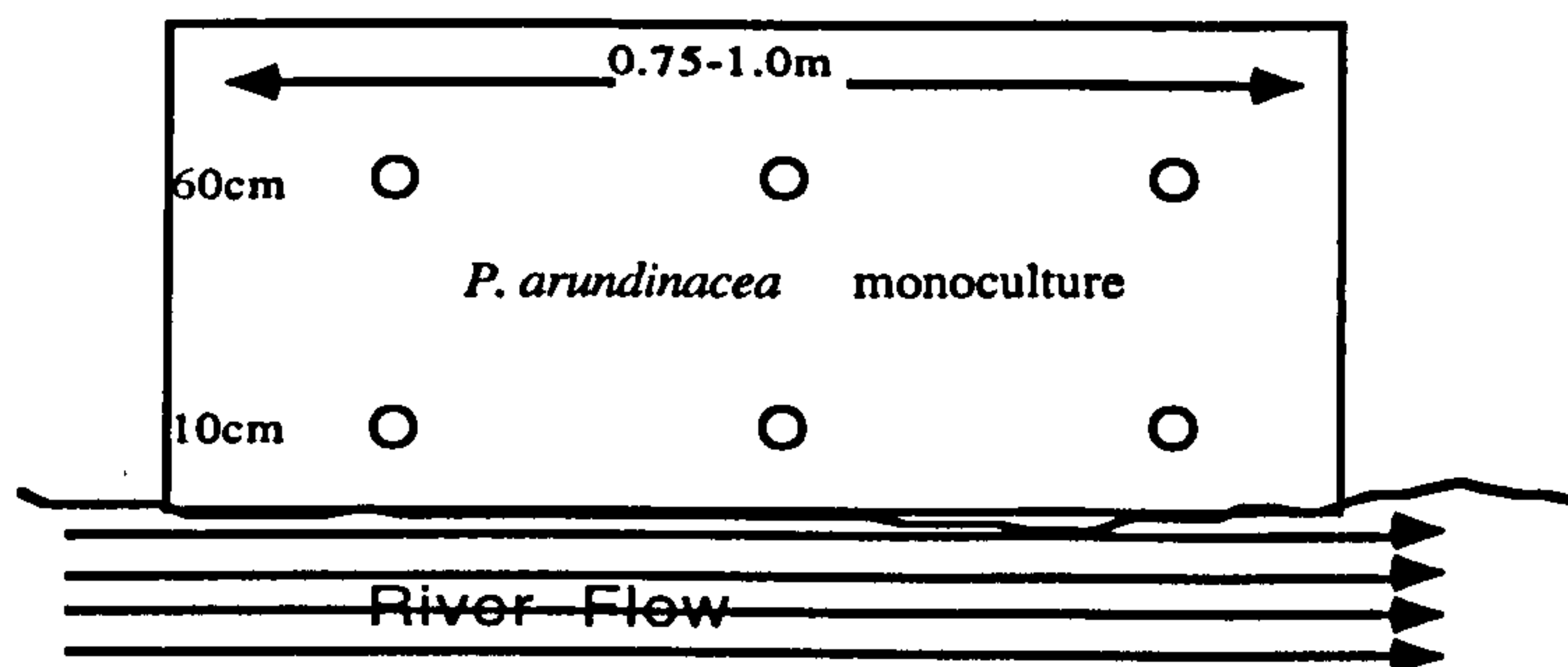


Fig. 6.2 : Sampling pattern for Shear strength, Moisture content and Total root length per unit volume of soil in a monoculture area of *Phalaris arundinacea*.

Sampling regime : An average of three measurements were taken within an imaginary circular area of 20cm radius. In total there were 3 readings/sampling points per position. There were 6 such positions as shown in Figure 6.2, for each plot. The total number of plots surveyed was three for each species.

b) Root Sampling

This was carried out immediately after the shear strength measurements and as near to the point of shear strength measurement as possible. Only one sample was taken per position due to the amount of time taken by one person carrying out the whole survey within a reasonable period of time. It was expected that the sampling point replication on the pre-planned grid pattern would be sufficient for a statistical analysis.

Sampling regime : For each position = (at 5cm depth, 1 sample; + at 10 -15cm depth, 1 sample;) = 2; Number of replicate positions per plot = 6; Number of replicate plots = 3; Hence, total number of soil cores for roots per species = 36

c) Moisture Content Sampling

Sampling was carried out on a sunny day with three previous days of no precipitation. Samples were taken in the immediate region that was subjected to shear strength and root sampling. The number of samples taken was one per point on the grid. As mentioned earlier, replicates were expected to be satisfactory in number as for root samples. Work carried out on moisture content measurements in the experimental regimes (see Chs. 3, 4 and 5) on the slope of the bank showed that there was no significant variability in moisture content laterally along the bank within an area of 5 x 5m as opposed to the highly significant variability vertically upwards along the bank.

Utmost care was taken not to destroy the vegetation or damage the bank by too much trampling or coring for samples.

6.4 Results

6.4.1 Analysis of results:

The analysis was developed as follows:

Step i) appraisal of the variability of each parameter (eg. the variability between root density at 5cm and 10-15cm); test of null hypothesis;

Step ii) statistical analysis to test the possibility of developing a theoretical model that represents a relationship between the three factors measured (i.e Shear strength, Moisture content and Total live root length per unit volume of soil).

N.B.: Due to the inherent diversity of the rooting characteristics for different species of plants, it may not be a universally acceptable model that incorporates the three factors of the soil. But, from the literature survey it was concluded that there was a necessity at that time to investigate the relationships as above. Later it was noted that other authors had carried out similar studies for two of these factors during the same time period i.e. Shear strength and Root density (Scholand et al., 1991). They concluded that for the species tested there was no correlation between increase in root density and shear strength increases.

- i. Comparison of total root length per unit volume of soil for each species at each of the two depths.
- ii. Plot the graphical relationships between the three factors for each of the three species. For example the relationship of shear strength and total root length per unit volume of soil for each species at each of the two depths.
- iii. Statistical analysis of the data for correlation between the factors of shear strength and total root length per unit volume of soil for each species, a comparison of means (t-test) for significant differences between species on total root length per unit volume and shear strength.

6.4.2 Analysis of total root length per unit volume soil for each species at two depths of the bank (intra-site vertical variability)

The reason for sampling root density at 5cm and 15cm depths from the surface of the bank was to initially identify whether there was a significant difference in the root density within each species and between species. If there is such a difference within a species, the presumption would be that it may influence both the shear strength of the soil at each depth and more significantly it may affect the erodibility of the bank. In terms of erodibility of the bank this study is prioritised to processes of corrosion and not necessarily the process of mass failure by rotational slips. Hence the depth of 15cm is considered sufficient. If there is a significant difference between the root densities at similar depths between species, then a series of possible implications are envisaged. These will be discussed later in the conclusions.

a) Root density at depths of 5cm and 15cm for *Phalaris arundinacea* :

As shown in Table 6.1.below, the t-test carried out indicates a non-significant (0.07) difference of root density between these two depths. The values for standard deviation together with the means for both depths are noteworthy in terms of the possible distribution of root density within the 5 - 15cm depth.

Phalaris arundinacea

Variable:	5cm	15cm		
Mean:	204.908	121.938	t-statistic:	1.855
Std. Deviation:	151.376	114.445	Degrees of Freedom:	34
Observations:	18	18	Significance:	0.072

Table 6.1 Results of statistical analysis of root length values for 5cm and 15cm depths for *P. arundinacea*.

b) Root density at depths of 5cm and 15cm for *Urtica dioica* :

For Stinging Nettle, *U. dioica* , there is a significant difference (0.010) of rooting density at the two depths.

Urtica dioica

Variable:	5cm	15cm		
Mean:	45.656	21.211	t-statistic:	2.747
Std. Deviation:	26.956	26.428	Degrees of Freedom:	34
Observations:	18	18	Significance:	0.010

Table 6.2 Results of statistical analysis of root length values for 5cm and 15cm depths for *U. dioica*

c) Root density at depths of 5cm and 15cm for *Epilobium hirsutum* :

For the Hairy Willow Herb, *E. hirsutum* , the difference between root densities at the two depths are highly significant.

Mean root length at two depths / *Epilobium hirsutum*

Variable:	5cm	15cm		
Mean:	51.933	26.233	t-statistic:	2.872
Std. Deviation:	30.964	21.971	Degrees of Freedom:	34
Observations:	18	18	Significance:	0.007

Table 6.3 Results of statistical analysis of root length values for 5cm and 15cm depths for *E. hirsutum*

Conclusions

- 1. There is a significant difference of root density distribution within the upper 20cm layer of bank soil for *E. hirsutum* and *U. dioica* but not for *P. arundinacea*.
- 2. *P. arundinacea* has the highest root density, which is always more than double that for each of the other species at any depth of the soil.

6.4.3 Analysis of total root length per unit volume of soil for each species at two heights up the bank for each species

The moisture content indicated a gradation profile upwards the bank (i.e. percentage moisture content gets lower in a step-wise manner) in the experiments (see Chs. 3, 4, & 5 above). Hence it would not be appropriate to compare either the root densities or the shear strength of the soil for all three species in permutations with their percentage moisture contents of the soil. This inconvenience is a reality in nature as opposed to experimental cultivations because *Phalaris arundinacea* is prevalent mostly in the bottom region of the waterways. The best one could do is to compare the three factors in the two species , *U. dioica* and *E. hirsutum*, that appear to share the same geomorphic niche i.e. the mid-region of the bank profile, and to identify any factors of geomorphic or ecological value.

a) Phalaris arundinacea :

Root density at 10cm and 60cm from the normal water level

Phalaris arundinacea		
Variable:	Phalaris/10cm	Phalaris/60cm
Mean:	181.107	145.739
Std. Deviation:	137.533	95.211
Observations:	9	9
t-statistic:	0.634	
Degrees of Freedom:	16	
Significance:	0.535	

Table 6.4 Results of statistical analysis of root length values for 10cm and 60cm from the bank waterline for *P. arundinacea*.

The null hypothesis has to be accepted because of the very low probability factor from the data analysed. This is not what was expected at the commencement of the survey. The hypothesis was that there would be a significant difference in root densities

at the top end of the monoculture as opposed to the water edge. The reason for such expectations arises from the apparent clumping effect of this species at the bottom edge of the river bank at maturity. Closer observation of the field data as well as the magnitudes of the standard deviations may well recommend a more extensive survey for definitive conclusions.

<i>Phalaris arundinacea</i>		
<u>% Moisture content</u>		
Variable:	P.a/MC/10cm	P.a/MC/60cm
Mean:	67.700	41.412
Std. Deviation:	8.002	8.040
Observations:	9	9
t-statistic:	6.952	Hypothesis:
Degrees of Freedom:	16	Ho: $\mu_1 = \mu_2$
Significance:	0.000	Ha: $\mu_1 \neq \mu_2$

Table 6.5 Results of statistical analysis of % Moisture contents at 10cm. and 60cm. from the bank waterline for *P. arundinacea*

<i>Phalaris arundinacea</i>		
Variable:	P.a/10cm/KPa	P.a/60cm/KPa
Mean:	57.667	68.963
Std. Deviation:	18.450	12.007
Observations:	9	9
t-statistic:	-1.539	
Degrees of Freedom:	16	
Significance:	0.143	

Table 6.6. Statistical significance of Shear strength values between 10cm and 60cm from the normal waterline of river.

Moisture Content and Shear Strength at 10cm and 60cm from the normal water level for :

(a)*Phalaris arundinacea*

The statistical significance of the moisture contents at the two edges of this monoculture are high while that for the shear strength at the corresponding positions are non significant. It is noteworthy that the shear strength values themselves are not as high as one would expect if a direct correlation between variation of shear strength and root density were to be presumed.

Conclusions : For *P. arundinacea* there are no significant differences in shear strengths or in root lengths per unit volume of soil between the two levels 10cm and 60cm from the waterline upwards the bank . But the percentage moisture content does vary quite significantly between the two levels.

(b) *Urtica dioica* :

Root density at 50cm and 100cm from the normal water level

Variable:	<u><i>U. dioica</i>/50cm</u>	<u><i>U.dioica</i>/100cm</u>	
Mean:	35.073	31.710	t-statistic: 0.365
Std. Deviation:	24.175	13.406	Degrees of Freedom: 16
Observations:	9	9	Significance: 0.720

Table 6.7 Statistical significance of root density of *U. dioica* at 50cm and 100cm from the normal waterlevel

Variable:	<u>U.d./%MC/50cm</u>	<u>%MC/100cm</u>	
Mean:	57.142	37.467	t-statistic: 3.777
Std. Deviation:	10.883	11.215	Degrees of Freedom: 16
Observations:	9	9	Significance: 0.002

Variable:	<u>U.d/kPa/50cm</u>	<u>kPa/100cm</u>	
Mean:	17.111	12.444	t-statistic: 1.961
Std. Deviation:	6.521	2.901	Degrees of Freedom: 16
Observations:	9	9	Significance: 0.067

Table 6.8 Statistical significance of (a) % Moisture content and (b) Shear strength, for *U. dioica* at 50cm and 100cm from the waterline

There is no marked significant difference between the rooting density of this species within the apparent monoclonal boundaries surveyed. It must be noted that Stinging nettle is not to be considered a wetland species merely because it is prevalent along the banks of the waterways in southern Britain. It is primarily an opportunistic species prevalent in soils of high nutrient status (Grime et al, 1986). The fact that the standard deviation of the root density is larger at the lower boundary may be an interesting topic of physiological implications when taken in conjunction with the significantly higher moisture content at this geomorphic position. It is at this height of the

bank that most of the concave subsidence of the mid profile of the bank was noted along this stretch of the river. For Site 2 this was noted in particular. In effect we are observing the rooting pattern at the lower end of a hollow at 50cm and the lower end of a hummock at the 100cm level.

It is interesting to note that while there is no significant difference of shear strength between the 50cm and the 100cm levels for *U.dioica*, the value is lower at the drier upper level. If the presumption is that lower moisture content is synonymous with higher shear strength in a clayey soil, and vice versa (Rosenak, 1963), then what these results indicate is that the higher root density at the 50cm level contributed to the increase in shear strength of the soil at this level.

(c) *Epilobium hirsutum*

Root density at 50cm and 100cm from the normal water level

Epilobium hirsutum

Variable:	E.h/50cm(L)	E.h/100cm(L)
Mean:	40.842	37.321
Std. Deviation:	21.210	25.625
Observations:	9	9
t-statistic:	0.318	
Degrees of Freedom:	16	
Significance:	0.755	

Table 6.9 Statistical significance of Root Density for *E. hirsutum* at 50cm and 100cm from the waterline

Epilobium hirsutum

Variable:	50cm(KPa)	100cm(KPa)
Mean:	22.481	35.370
Std. Deviation:	10.195	12.069
Observations:	9	9
t-statistic:	-2.447	
Degrees of Freedom:	16	
Significance:	0.026	

Table 6.10 Statistical significance of Shear strength variations under *E. hirsutum* at 50cm and 100cm from the bank waterline

Epilobium hirsutum

Variable:	50cm(MC)	100cm(MC)
Mean:	58.272	45.563
Std. Deviation:	10.318	9.328
Observations:	9	9
t-statistic:	2.741	
Degrees of Freedom:	16	
Significance:	0.014	

Table 6.11 Statistical significance of % moisture content under *E. hirsutum* at 50cm and 100cm from the bank waterline

There is no significant difference in the root densities of *E. hirsutum* within its habitat boundaries. The variation of moisture content between the upper and lower boundary region is more marked than the variation of shear strength of the soil. But, it is noteworthy that the overall shear strength of the soil which this species colonises has much higher values at 100cm level than those corresponding for *U. dioica* which occupies the same position on the bank profile even though both species appear to have very similar root densities. This may be a reflection of differential tensile strengths of the roots of the two species if the presumption is that roots *per se* have an influence on the variations of shear strength of the soil.

Moisture content alone may have explained the shear strength differences at 50 and 100cm but for the fact that Moisture content is closely similar for *E. hirsutum* and *U. dioica*. Therefore it has to be suggested that it is a feature of the root systems not reflected in simple root density.

Phalaris arundinacea

1

DF:	R:	R-squared:	Adj. R-squared:	Std. Error:
17	.497	.247	.147	14.946

Analysis of Variance Table

Source	DF:	Sum Squares:	Mean Square:	F-test:
REGRESSION	2	1100.128	550.064	2.462
RESIDUAL	15	3350.866	223.391	p = .1189
TOTAL	17	4450.994		

Table 6.12 Fitted model of shear strength as a function of % moisture content and root length per unit volume of soil for *P. arundinacea*.

Urtica dioica

Multiple Regression Y ₁ :Column 5 2 X variables				
DF:	R:	R-squared:	Adj. R-squared:	Std. Error:
17	.583	.34	.252	4.716

Analysis of Variance Table				
Source	DF:	Sum Squares:	Mean Square:	F-test:
REGRESSION	2	171.924	85.962	3.865
RESIDUAL	15	333.631	22.242	p = .0443
TOTAL	17	505.556		

Table 6.13 Fitted model of shear strength as a function of % moisture content and root length per unit volume of soil for *U. dioica*.

Epilobium hirsutum

Multiple Regression Y ₁ :Column 8 2 X variables				
DF:	R:	R-squared:	Adj. R-squared:	Std. Error:
17	.841	.708	.669	7.309

Analysis of Variance Table				
Source	DF:	Sum Squares:	Mean Square:	F-test:
REGRESSION	2	1942.951	971.476	18.183
RESIDUAL	15	801.395	53.426	p = 1.0000E-4
TOTAL	17	2744.346		

Table 6.14 Fitted model of shear strength as a function of % moisture content and root length per unit volume of soil

As the F-values of the regression models indicate *P. arundinacea* does not impart a significant shear strength appreciation by virtue of its presence. It has the lowest relationship in terms of moisture content and root density in terms of shear strength.

For *U.dioica* there is a significant relationship approximating 95 percent confidence limit. But for *E. hirsutum* the effect of roots and moisture content is the most noticeable, with an F-value of 18.183.

6.5 Final conclusions

What is statistically significant in this survey confirms the views expressed in the analysis of the results and the discussions in the experiments 1, 2 and 3. of Chapters 3, 4 and 5.

As mentioned in Chapter 4, there has to be an explanation as to how and why *P. arundinacea* does not on the one hand increase the shear strength of the soil proportionately with the increase in the root length per unit volume of soil but on the other hand arrests active bank erosion in a few months and prevents potential erosion during subsequent high flows. If the theory is that roots *per se* increase shear strength of the soil (which is doubtful from the results of this study), then what this study proves is :

i) that increase of root density does not necessarily increase the shear strength of the soil proportionately; Smirnoff and Crawford (1982) finding of increased production of aerenchyma in *P. arundinacea* roots after inundation may be offered as an explanation of high root density associated with mediocre shear strength values imparted by this species because aerenchymatous tissue cannot be proposed as high tensile material.

Further research on the properties of the roots and rhizomes of this species of wetland grass must be carried out. Such a study should encompass not only factors related to shear strength (tensile strength and cohesion) but also other propositions such as 'soil aggregate stability' (Reid and Goss, 1981), seasonal root turnover and any soil protecting (Turmanina, 1965) morphological attributes of an 'edapho-ecotropic' nature (Vanicek, 1973).

ii) that lower root density does not necessarily mean a lower shear strength imparted to the soil by a plant species. *E. hirsutum* in fact has much less root density than *P. arundinacea*. However, the former imparts a higher shear strength from a few roots. This may be linked to other intrinsic factors such as tensile strength of the roots;

iii) the fact that a species such as *E. hirsutum* does impart a significant increase in shear strength of the bank soil does not mean that it is better than a high root density species such as *P. arundinacea* in preventing bank erosion. In fact the latter species is better at prevention of erosion as discussed in Chapter 4 ;

In essence, the first hypothesis proposed and tested in this study (see 1.6) on the relationship between shear strength of the soil and the root density of the species occupying the soil is discounted. On the whole, there is no clear evidence of increases in bank shear strength values under either *Epilobium hirsutum* or *Urtica dioica* as the variations may be due to the higher (and drier) positions they occupy on the river bank. For *Phalaris arundinacea* the higher shear strength values in their rhizosphere are attributable to higher root density. In addition to this the arguments for adaptive strategies of different species with inherent morphological adaptations such as root mattings (in *Phalaris arundinacea*), and other 'edaphoecotropic' (Vanicek, 1973), attributes need to be explored.

Ch. 7. Discussion and implications

An appraisal of the inter-relationships of the experiments and survey; theoretical and applied implications in practice (Bank stability, aesthetic values, ecological values, economic values); Future directions;

7. 1 Test of Hypotheses:

In the introduction, the literature survey identified the background to the state of scientific understanding on the main parameters defining this proposal. Based on that evidence certain hypotheses were deduced (see 1.6) for verification/falsification. In 1.2.3 and 1.6 questions of a wider implication were posed. The discussion hereafter shall concentrate on a re-assessment of the results, observations and photographic evidence to ascertain:

- i. whether the hypotheses have been verified/falsified;
- ii. to what extent the questions have been answered;
- iii. whether the aims of the study have been fulfilled;
- iv. what general synthesis can be made of the main conclusions from the three experiments and the survey

The first exercise is a field test of an otherwise empirical hypothesis proposed and accepted for dryland vegetation. It proposes that

(a) increases in root density are reflected in higher shear strength of the soil; (tested in Experiments 1 and 2 and the survey; see 3.4.4.; 4.5; and Ch. 6);

(b) high shear strength of the soil is indicative of less erodibility of the soil; (tested in Experiments 1 and 2; see 3.4.3 and 4.5.1);

The results of experiments 1, 2 and the the survey have been analysed and discussed in Chapters 3, 4 and 6. They consistently indicate that the above hypotheses cannot be accepted for vegetation on a slope of a river bank. While there are a few instances of correlations of soil shear strength and total length of roots these are rare and inconsistent. For example there is no such correlation for either monoculture bank vegetation (see *P. arundinacea* in 4.5.2) or mixed bank vegetation (see natural vegetation dominated by *U. dioica* and *E. hirsutum* in 3.4.4a to 3.4.4c).

Concurrently, there is significant reduction of bank erosion by all three types of vegetation studied i.e. Natural vegetation dominated by *U dioica*, Natural vegetation dominated by *E. hirsutum* (see Ch. 3) and banks cultivated by a monoculture of *P. arundinacea*.(see Ch.4) irrespective of any relationship between the amount of roots in the bank soil and its shear strength. As such the hypothesis that negation of bank erosion under flooded conditions is attributable to the stabilisation of the banks by roots primarily by imparting a positive effect on increases in shear strength of the soil has to be rejected.

It may be suggested that a drawback in the study of secondary succession is that root densities were not quantified at any stage. The main reason for this is the expectation of a diverse range of pioneer colonisers within the experimental plots and hence the inability to correlate positional shear strength values to specific coloniser species. For example, if within the sheared soil area (say 10-15cm) there were three or four species of plants present, then there would be an inability to identify to which particular species the shear strength may be attributed to. There was no such complexity in the cultivated *P. arundinacea* plots or the Natural vegetation dominated by *U. dioica* or *E. hirsutum* species. Therefore it is not possible to discuss whether the process of secondary succession is associated with pioneer species which have high root densities in the top soil. It is noteworthy that plants such as *Cirsium arvense* and *Rumex acetosa* are renowned for deep rooting but not necessarily of high root density at a given stratum of soil.

The question may arise that in this study the hypothesis of effects of roots in negating erosion is already discounted. It has to be borne in mind that what has been falsified is that the roots do not increase the shear strength of the bank. The dilemma is that there are other proposals on root effects in consolidation of soil. These encompass factors not necessarily related to shear strength but others such as 'soil aggregate stability' (Reid and Goss, 1981), seasonal root turnover, soil protecting root curvatures (Turmanina, 1965) and other morphological attributes of an 'edapho-ecotropic' nature (Vanicek, 1973). It is not intended to discuss these theories here due to their scope beyond the exercise of this project.

Rejection of the pre-experimental hypothesis as a conclusion arising from the analysis of the experimental results, and the discussion of observations does not necessarily terminate the importance of bank vegetation as a negator of bank erosion. What it implies is that research has, so far, been oriented towards the theoretically feasible and laboratory tested models of root effects on prevention of erosion (cf. Kassif and Kopelovitz, 1968; Waldron, 1977, Waldron and Dakessian, 1982) which may not hold true in the field as confirmed in this study and Scholand et al.(1991). The aspect of the conflict between modellers and experimentalists is well discussed by Boardman et al (1990) as discussed earlier. In this study Mohr Coulomb equation was not contested theoretically. The dependence by others on explaining reduction of land erosion purely as a contribution of the root system of a plant was questioned. The inconsistency of root densities within a given volume of bank soil at different heights of the banks as opposed to closely consistent values of shear strengths at the same positions of the bank is exposed.

The second hypothesis proposes that *"the shoot system is associated with reduced bank erodibility; it acts as a physical barrier between the motive fluvial forces and the resistive bank soil; "(tested in Experiments 1, 2 and 3; see 3.4.2; 4.4; and 5.4);*

The test of this hypothesis is mainly dependent on the argument that even though the first hypothesis was falsified (roots *per se* do not necessarily increase the shear strength and thereby decrease the erodibility of the bank) the erosion rates under bank vegetation were significantly reduced. The inference is that in the absence of any other feasible phenomenon to explain the reduction of erosion, the shoot system is proposed to be the key factor for the reduction in bank erosion. The discussion therefore is extended to identify whether different vegetation types offer species specific strategies in terms of the phyllospheric cover/ground cover offered seasonally or through the stages of colonisation of a river bank.

In this discussion the role of the shoot system is addressed primarily from a physical perspective. It is an attempt to simplify the (associated biological and ecological) complexities presented in assessing erosion under three possible types of vegetated channel banks:

i. normal vegetation (long-established bank vegetation that has a few species which are identified as spatially dominant over the major surface profile of the banks; see Plates 5 and 6);

ii. artificially cultivated monoculture (*P. arundinacea* from uniform seeding > seedling > maturity); this expects an initial *uniform establishment of plants*; as all plants are of the same species, at any given time the ground cover offered by the foliage should be uniform as the leaf area ratio and leaf orientation will be species specific;

iii. naturally re-vegetated banks (secondary succession)

This expects *non-uniform spatial colonisation*, multi-species colonisation, rapid turnover of species as a result of intra and inter-specific competition. The overall physical effect expected is one of varying ground cover and heights of plants. (in contrast to that of a monoculture in ii above).

Through the 25 months of the project, the *Normal vegetation* presented two distinct physical phenomena in keeping with temperate seasonality. In summer the foliage was dense, tall (c. 1.5m in height) and offered maximum ground cover. In winter they were defoliated in the deciduous species (eg. *U. dioica* and *E. hirsutum*) in contrast to the non-defoliated, (senile but leafy) grassy species. Another observation which may have significant relevance in terms of prevention of bank erosion was that the fallen dead leaves of the deciduous species formed an intricate and sometimes deep litter on the otherwise exposed bank surface. The result of the first flood of the river was to flatten the erect dead stems of the deciduous plants onto the bank surface (see plate 14). The final outcome was that while some of the dead leaves were washed down the river, others were flattened onto the bank surface as a result of the flattening of the dead stems on them. In effect, the result was the formation of an effective physical intermediary between the erosive fluvial forces of the floods and the bank soil surface.

In terms of the degree of effectiveness against bank erosion, the quantified comparisons were analysed and conclusions were made in Chs. 3, 4 and 5. Specific conclusions in 3.4.2a, 3.4.2e indicate (a) the effectiveness of the physical presence of vegetation on the mid to upper banks as an efficient negator of erosion (see further discussions below in 7.2, and 7.3), and (b) the need for the encouragement of fringe

vegetation at the bank-toe primarily as a negator of toe erosion and possible subsequent pseudo-cyclic erosion;

Attempts to address erosion under ideal conditions of shoot cover (phyllospheric uniformity) by artificial cultivation of *P. arundinacea* were thwarted by (a) the wash away of some of the originally seeded toe-region, (b) wash away of some seedlings by fluctuating channel flow regimes and (c) the need to re-seed periodically until mid-summer of 1977. This was reflected in higher eroion rates than expected as analysed and concluded in Ch.4. In addition, the following observations are of of significance:

- i. *P. arundinacea* initially establishes more uniformly in the upper regions of a river bank; however there is a final preference for long term establishment at the toe-region (see Plate 8); This characteristic signifies the species-specific suitability for prevention of erosion in the lower banks.
- ii. the physical barrier created between the bank soil and the water during winter high flows is much thicker as *P. arundinacea* was observed to die-back with a thicker foliage and detritus (compared with *U. dioica* and *E. hirsutum* dominated banks) during this season.

Secondary succession is a natural phenomenon on a disturbed soil. The questions posed here are (i) whether the ground cover, (as opposed to rooting characteristics) offered by the coloniser species are effective negators of bank erosion? (ii) how effective were they? (iii) is there a high turnover of species in temporal and spatial aspects? (iv) are these temporal and spatial changes reflective of a strategy to consolidate their hazardous habitat (i.e. the river bank)?

In the analysis of results on erosion rates over the 25 months of this study (see Ch.5) it was concluded that secondary succession is an effective negator of erosion. The degree of effectiveness is comparable with the artificial cultivation of a wetland grass monoculture as mentioned in the conclusions for Ch. 5.

The discussion is based on the observed species and their species-specific characteristics in terms of ground cover. The aim of identification of primary colonisers was to gain an understanding of aspects hitherto unidentified by other authors (i.e. leaf orientation in terms of ground cover and pioneer coloniser species and their implications

in preventing surficial erosion on channel banks). Such preliminary observations would hopefully identify the necessity for an intensive large scale study of the subject.

Of the species observed in April 1987 (see App. 7a) *Taraxacum spp.*, *Rumex spp.*, *Solidago spp.* and *Cirsium spp.* have their first leaves oriented flat on the ground. This is in contrast to species such as *P. arundinacea* which have young seedling leaves that are filiform and oriented upwards thereby offering less ground cover per seedling/young plant. The inference is that erosion of a newly bared bank is arrested within a season of re-vegetation because of the high frequency of pioneer colonisers with young shoot systems that offer very high ground cover (see Plates 10 and 12).

From a process identification aspect, the observation that recolonisation (shoot cover above ground) appears to initiate from the bank-toe to bank apex in a sequential manner has been discussed in Ch. 5. The suggestion is that this phenomenon consolidates the bank and prevents continuing lower bank destability. It may also be suggested that this strategy prevents cyclic de-stability of the lower >upper >lowerbank erosion and collapse. It offers an efficient physical barrier at the bank-toe region to prevent the cycle of erosion. The physical presence of the shoots at the bank base also acts as a trap for silt and soil eroded from the upper bank.

The third hypothesis is that *effects of the shoot system and the root system are not considered as mutually exclusive (i.e. they act in unison) in terms of channel bank erosion*

The discussion hereafter shall concentrate on a re-assessment of the results, observations and photographic evidence in search of two fundamental aspects of functional significance of bank vegetation with relevance to prevention of bank erosion.

The falsification of the first hypothesis only proves that root effects through shear strength of the bank soil may be discounted. It does not imply that roots may not have any other contributory role to prevent erosion of the channel bank. The first objective is to evaluate what other role/s roots and root systems of bank vegetation may play in prevention of bank erosion.

In this study there were live roots observed for different vegetative types (eg. Natural vegetation dominated by *U. dioica*, Natural vegetation dominated by *E. hirsutum*

and banks cultivated by a monoculture of *P. arundinacea*.). There were differing amounts of live roots per unit volume of soil depending on the season of the year (see sections 3.4.4a to 3.4.4c; Figs. 3.13b, 3.13c, 3.14b, 3.14c, 3.15b, 3.15c, and section 4.5.2 with Figs. 4.14, 4.15, and 4.16). It is quite clear that all these vegetation types had significant amounts of live roots not only during the highly erosive winter period but also at the end of one of the longest flooded periods for this river.

In the case of the non-deciduous plants such as *P. arundinacea*, the first floods flattened the erect stems, with the senile leaves attached to them, on to the bank surface. In this case the dead foliage 'barrier' created in this process was observed to be much thicker thereby minimising any erosive forces from the channel flow to act directly on the bank surface.

Plate 14 (plot dominated by *U. dioica*) and plate 15 (plot dominated by *E. hirsutum*) which were taken on opposite sides of the river in February 1988 , at the cessation of the long winter flood, clearly show the presence of the dead vegetation which had neither washed down the river after four months of resurgent floods nor decayed totally. In fact, both plates bear evidence of 'silt trapping' within the dead foliage. This is of significance both in deposition (as opposed to erosion) as a physical phenomenon of geomorphological significance as well as nutrient enrichment as a phenomenon of plant biological significance. While there is no evidence for either uprooting of vegetation or bank erosion in the vegetated mid to upper bank region, both show evidence of two processes of bank erosion at the toe-region which was devoid of vegetation (patchy erosion in plate 14 and undercutting in plate 15).

So far we have made two conclusions. The first is that there are live roots in the rhizospheric area of the bank soil under vegetation irrespective of the species of vegetation under study The second is that the fluvially assisted physical re-orientation of the phyllosphere serves as a mechanism for prevention of erosion and a positive contribution (silt entrapment and deposition) to bank geometry. The next stage is to appraise whether the live roots of the vegetation, which has a dead/senile shoot system have any contribution to bank stability. Are they an important or in fact a *sine qua non*

component to retention of the dead/senile shoots that form the covering layer on the bank surface?

In the light of the comparisons made of observations, photographic evidence and analysis of results, it is conclusive that the root systems in the naturally vegetated banks were instrumental in anchorage of the surficial dead foliage on the bank surface thereby contributing to prevention of bank erosion during winter floods. The comparison in Table 7 below, depicts factors associated with and erosive processes under (a) seasonal die-back in normal vegetation and (b) systemic induced death of vegetation. This enhances the hypothesis that a root system is necessary at least for anchorage of the shoot system so that the latter may prevail as a physical entity on the bank. This physical barrier thereby prevents the erosion of the bank.

The next stage is to identify whether the roots that prevail during the winter bear any species-specific characteristics that enhance their role in retention of the above ground foliage during varying storm flows. Is it simply the amount of total live root lengths per unit volume of soil, their tensile properties or their rooting pattern (tap root systems, fibrous root systems or either/both with rhizomes and tubers) that would ensure optimal performance? As shear strength increases are discounted in this study, an experiment that incorporates the above factors is recommended as a future study.

This comparison of results and observations and the preceding discussion of other results with reference to hypothesis 3 (root system and the shoot system act in unison in preventing channel bank erosion) leads to an acceptance of it. However, it is hoped that this identification of the operative processes and key factors derived from the results, and observations may form a scientific explanation (Boardman et al, 1990) as a preliminary to effective future modelling.

Natural die-back of Normal vegetation in winter	Systemic herbicide-induced total denudation in summer
i. total defoliation associated with deciduous plants in autumn and winter;	i. immediate total death followed by defoliation
ii. stems left as erect, dead shoots; they are well attached to the root system of the plant;	ii. stems left as erect shoots initially; within a few weeks shoots are brittle in texture and break down;
iii. root system active; (see discussion in 3.4.4)	iii. root system completely dead
iv. winter floods flatten the dead foliage onto the bank surface forming a 'pseudo matting' of skeletal dead vegetation cover on the bank (see plates 14 & 16) with minimal breakaway of dead shoots; closer observation reveals that all dead shoots are still anchored to the ground via the roots;	iv. first inundation (irrespective of season) clears much of the dead shoots on the bank surface; this exposes the bank surface to direct fluvial shear forces;
v. no slumping observed within experimental area;	v. slumping observed (see plate 13); closer observation revealed numerous dead roots in the remaining bank overhang as well as in the eroded soil slump lying at bottom of the bank. exposed roots were brittle;
vi. long-term submergence/flood has minimal erosive effects in the well vegetated mid to upper bank region (see discussion in 3.4.2a to 3.4.2g);	vi. long-term inundation is highly erosive for this bank. There is no flattened dead vegetative-cover acting as a protective matting on the bank surface (see discussion in 3.4.2.a to 3.4.2g and plate 4);
vii. bank-toe region is subjected to patchy erosion (see plate 14) if either there is absence of dead vegetative cover or the original (pre-inundation) dead skeletal cover is forced upwards to mid-bank from the toe-region of the bank;	vii. patchy erosion is superseded by slumping and wash away of bank in bulk. (see Plate 13);
viii. seasonal changes from winter floods to spring ambient flow regimes bring about a rapid acceleration of growth of fresh vegetative cover from the roots and rhizomes on this bank;	viii. seasonal changes are not directly associated with a resurgence of vegetative cover. It is more a process of secondary succession (see discussion in 5.4.2a to 5.4.2j, and plates 10, 11 and 12);
ix. spring vegetative re-growth occurs through the matting of previous winter's dead vegetation; closer observation indicated that the dead foliage had acted as a silt trap during winter floods (see plate 16); even though this study did not address the nutrient aspects of post-inundation growth of bank vegetation, a future study may be directed at assessing the soil enrichment and the role of dead vegetation matting in both soil enrichment and as a trap for floating vegetative propagules on the bank.	ix. spring vegetative growth occurs on bare soil with no surface matting that may aid in conservation of steep upper-bank soil as stable habitats for new species to establish (see plate 11); this enhances patchy erosion during summer floods (a serious implication for tropical irrigation canal banks if natural secondary succession is to be the implemented policy);
x. post-inundation (winter flood) regrowth of bank species of vegetation was mainly the same as pre-winter species;	x. post-inundation (irrespective of season) regrowth (secondary succession) of vegetation is different from the previous vegetation (see plate 10 and Appendix 7);
xi. dense uniform re-vegetation; fast process of ground cover by foliage;	xi. thin irregular re-vegetation; slow process of ground cover by foliage;

Table 7. A comparison of factors associated with and erosive processes under (a) seasonal die-back of Normal vegetation and (b) systemic herbicide-induced death of bank vegetation



Plate 13. Mid-bank slumping as a result of denudation by a systemic herbicide



Plate 14. **Corrasion in the lower bank region of Normal vegetation due to lack of ban-toe fringe vegetation (post-flood period Oct. 1977 to Feb. 1988)**
N.B. matting of dead winter foliage oriented down river on the bank forming a 'protective cover/barrier)



Plate 15. Undercutting at bank-toe of long established Normal vegetation;
 Observe lack of fringe vegetation
 N.B. dead skeletal shoot system (a) covering the bank, and (b) acting as a silt trap

It is considered relevant to discuss the overview of results, observations and their implications of each experiment through the following *interactive expose*.

7.2 Natural bank vegetation in relation to denudation

1) *Are the effects of bank vegetation a highly significant factor in discussing erosion or potential erodibility of bank soil ?*

There is conclusive quantitative evidence in this study to prove that :

- a) during winter newly denuded banks are seven times more erodible than the naturally vegetated banks on this stretch of the river Ouzel (see : 3.4.2f);
- b) any position on the upper zones of a newly denuded (by systemic herbicide) previously naturally vegetated bank would yield almost four times (3.56 in this study) the sediment yield of a similar position in the toe-region, under normal winter flow

This indicates the serious erosive implications in terms of bank erosion as induced by the practice of herbicide application on channel banks. The long-term implications on added sediment load to the river and channel sinuosity are worthy of consideration in formulating optimal guidelines on river system management.

2) *During a long-term flood, how does a naturally vegetated bank fare in terms of bank erosion?*

In 3.4. 2f, it was shown that the *lower bank* (toe-region) is three times more erodible than the upper regions of naturally vegetated banks during a long flood event like in 1987/88. On a comparable basis, under a normal winter flow regime as seen in 1986/87, the lower banks of the river eroded six times more than the upper bank. At face value this is questionable because the severity of the floods was much less during the 1986/87 winter than that of 1987/88. However a closer analysis indicates that in the 1987/88 winter, under the long flood regime there was approximately twice the amount of erosion in the upper banks than in the previous winter. This is ascribed to both the continuous high flows and the bank instability caused by root and shoot death and decay on the upper banks brought about presumably by the anaerobic conditions imposed by long submergence.

The long-term implications of *undercutting* as a result of competitive exclusion of fringe vegetation by certain upper bank species has been discussed in 3.4.2f. As the long

established naturally vegetated banks were devoid of fringe vegetation a proper comparison in terms of erosion between the upper and lower banks as 'vegetated banks' under long term floods is not feasible. The experience herewith and the enormity of the relative rates of increased erosion in the toe-region suggests a necessity to address this in a future study. Ideally the experiment should be carried out with a monoculture of a fringe vegetation. This would minimise the diverse morphological complexities that may complicate the analysis of the results as attributed to the fringe vegetation.

Natural occurrences of ecological significance may be proposed as a main cause of channel bank instability in the *middle to upper bank region*. It may be suggested that long-term floods can cause loss of an effective physical barrier offered by naturally vegetated banks; it is attributable to possible root death among non-semi-aquatic plants that use the bank as 'opportunistic' colonisers but lack the physiological ability to adapt to long-term submergence; the result is that they decay and wash away within a short time leaving an exposed, saturated, vulnerable bank. It is relevant to address Hooke'(1977a) observation that 'floods may have initiated erosion by removing vegetation and attacking stable banks" in the context of relative 'weaknesses' of some bank species. If early root death of a species reflects lack of phenotypic adaptations to floods and associated anaerobic, waterlogged conditions, then death and decay is the immediate result. This is followed by wash away of the decaying shoot system in the absence of any roots to anchor the dead foliage. The final result is an exposed area of bare bank which would be prone to erosion due to the high saturation. Authors who studied bare bank erosion (Hooke, 1977a) have concluded that newly exposed banks are pre-conditioned by saturation (weakened) as a result of initial high flows which is considered a prime factor for bank erosion by subsequent high flows.

An indication on the *relative susceptibilities of species* to long-term floods was evident in the root length data for Normal vegetation treatments. Following long submergence, on a comparative basis, *Urtica dioica* -dominated banks appear to have a higher loss of live root density and shear strength than *Epilobium hirsutum* dominated banks. What this confirms is that species-specific root characteristics are evident in this study. On the whole *P. arundinacea* is the most adaptive to long-term floods. The next in

order is *E. hirsutum* while *U. dioica* indicates the poorest performance, of the three species. The implications in terms of recommendations of species to be used as effective bank liners are self evident.

With reference to *post-submergence state of the naturally vegetated banks* two factors are considered of long-term significance. Once the floods have receded live root density and the shear strength of the soil suffer a delayed period of increase in values. It may be implied that such a bank may theoretically be classified as a 'weakened' bank based in terms of civil engineering terminology of shear strength. But, the long-term stability as tested by the flood proves that the bank was more stable (than would be otherwise expected if theoretical civil engineering models are to be relied on) even under low shear strength values. As such the critical limits for erosion are quite different with naturally well-vegetated banks when compared with a similar bank that is bare. The shear strength of the former may be lowered but stability is maintained by other factors attributed to the vegetation. The resurgence in both live root density and the spring growth of foliage indicates that the plants demonstrate the fundamental capability to restore the critical factors that negate erosion (physical barrier through foliage and anchorage of it through the roots).

3).What are the short-term effects of systemic herbicide application on bank vegetation ?

- a) The most susceptible period for erosion of a river bank is the first incidence of high discharge following denudation by a process of application of a systemic herbicide on existing vegetation (see discussions of Phase 1 of the experiments). The main implication is that the initial period of 3-4 months after denudation may create changes in soil physical properties which encourage erodibility by virtue of either the loss of tensile strength of dying roots and/or the creation of air spaces in the soil by decay of the roots ;
- b) the initial period of shoot death may not necessarily lead to immediate bank soil erodibility by fluvial action (see 3.4.2a). It is the secondary phase of root death which enhances the above process. This implies that anchorage of the dead foliage by the roots is critical for the presence or removal of the foliage which will offer ground cover or expose the bank to erosion.

c) initial erosion is much higher in the upper region of the bare banks than the toe-region (see 3.4.2c). It is suggested that the upper banks are more dependent on vegetation as soil is less adapted to inundation than the lower banks. In effect it may be a differential effect due to herbicide application (i.e. it may be a direct result of the virtual absence of any semi-aquatic fringe vegetation on this stretch of the river thereby causing more instability by plant death in the upper regions whereas the toe-region had a long established erodible or non-erodible nature arising purely out of its soil physical characteristics;). It may also be an inherent aspect of experimental error brought about by the erosion-pin technique in pins being covered by the falling debris from above.

d) for a newly denuded bank, a higher mean long-term discharge causes a higher erosion than a short-term period of high intensity discharge (see 3.4.2f);

It is clear from the shear strength and root density studies (see 3.5.3 and 3.5.4) that the bare banks do not have a much lower shear strength in August 1986 (Fig.3.7a) in comparison with the naturally vegetated banks (Figs. 3.7.b and 3.7c) but within the next month the erosion rates increased considerably under similar ambient flow regimes. This may have been the critical period of the effects of death of the roots on shear strength of the soil consequent to denudation. This emphasises the need for an intensive short-term study in the future to account for the death of different species of bank vegetation and the critical aspects of the soil (other than shear strength) attributable to the death of the roots.

7.3 : Cultivation of *Phalaris arundinacea* as a bank protector

P. arundinacea has been relevant to this study in two ways. It is a type of bank vegetation that is a natural coloniser of banks (Grime, Hodgson and Hunt,1986) as well as being a species recommended by hydraulics consultants (c.f.i Hemphill and Bramley, 1989). The accent in this study is more on the variation of shear strength arising from the roots of such a vegetation than the study of friction coefficient (Manning's N) for predictive formulations. It also takes into account the necessity for a species of grass which has a proven preference for the wetter lower regions of the bank while tolerating the possible existence on the drier upper regions or the temporary dryness of an ephemeral stream. Hence, the discussion will be more on this species of plant as an

inherently adaptive one to the fluvial ecosystem in comparison with other bank vegetation.

i) Is *P. arundinacea* better than naturally established vegetation in prevention of channel bank erosion ?

a) on a comparative basis *P. arundinacea*, once established on the banks, reduces erosion to the levels of normal bank vegetation (see 4.5.2b). It must be remembered that in this experiment *P. arundinacea* was subjected to a critical test of long-term submergence within a few months of its establishment in the summer of 1987. In effect, it clearly indicates a high efficiency as a bank liner in a short period of time. The applicability of such a species lies in its suitability for such waterways as irrigation channels and diversions of small channels or rivers where the riparian authorities can allow only a limited period of time for establishment of an effective bank vegetation that would prevent erosion with initial and subsequent high discharges.

b) upper bank erosion is almost totally arrested by this species in the establishment within one season where the prevalent fluctuations in discharge of the channel were not conducive to seedling establishment in the lower bank. The second summer of growth (by July 1988) is associated with the colonisation of the toe-region (see Plate 8). This proves that even though the toe-region colonisation during the first summer of growth was impaired due to flow conditions, subsequent vegetative reproduction assures the colonisation of this region. It also proves that *P. arundinacea* is a true wetland species of grass which colonises the bank-toe region not because of being competed out from the upper banks by other species but because it prefers the fringe habitat. As Plate 4.2 shows this colonisation of the toe-region occurred when the upper bank also was a monoculture of the same species (i.e. in the absence of competition).

ii) Does *P. arundinacea* impart any characteristics that will enhance the stability of the bank through increases in shear strength values ?

a) the first year of growth indicates an increase of shear strength but only up to that of normal bank vegetation . This does not necessarily mean that it should increase the shear strength of the soil in proportion with the increase in root density. It must be stressed that a bank may be subjected to two broadbased phenomena of erosion, i.e. corrosion

and slumping (Hooke, 1977a). The critical limits for the two processes are different. In this study we are interested in soil stability in terms of the motive force of the water and the resistive force of the bank soil. As long as the critical limit above bank failure by corrasion and slumping due to the maximum possible discharge in the channel is attained the plant would be imparting excessive shear strengths to the soil which would not be necessary. Theoretically this should be sufficient for bank vegetation that does not present a threat to the stability of the bank by virtue of its weight. If it was a tree then an increase in tensile properties of roots and shear strength should be expected with the increase in height and weight to account for both wind erosion and gravitational pull aspects (De Ploey, 1981).

iii) Is *P.arundinacea* of value to the bank stability from aspects other than shear strength ?

A host of relevant ecological aspects are worthy of consideration:

a) It is a highly competitive species (Grime, Hodgson and Hunt, 1986 and as proved by the colonisation of the upper and lower banks consecutively in this experiment). It colonises the upper banks initially * to establish its seedlings which are in the safer (from fluctuating channel discharges) upper regions. Once established it rapidly (in one season, as noted in this experiment) colonises the lower banks which are its preferred long-term habitat. Such modes of colonisation lead to suitable habitat creation for nests of birds that frequent the waterway.

(* under the broadcast seeding method practised in this experiment this has been proven; there is no evidence to believe that it would do otherwise in natural seed propagule dispersal and seedling establishment).

b) the lower region of the bank shows a significant reduction in erodibility only at the end of the second season of growth. This may be a reflection of late colonisation by established plants from above, together with an initial inability for this species to germinate from seeds at the fluctuating flow levels at the toe region. The possible implications of acting as a barrier against winter fluvial shearing stress, or the root system acting as a 'cushion' against the fluvial forces have been discussed in 4.5.2.(b)

c) The issue of the measure of shear strength as an indicator of soil stability was discussed earlier as a contentious issue. It was also pointed out that increase in root density is not necessarily well reflected in corresponding increases in bank shear strength values. As the root density of *P. arundinacea* has been shown to be high even during a winter of long floods (see 4.5.4) the factor of importance is the possible role that the *P. arundinacea* root system plays in storage of energy (harvested by photosynthesis in summer) during the winter. *P. arundinacea* has a well ramified root system that develops rhizomes both for vegetative reproduction and storage and translocation of food.

From the observations of the experiment and the theoretical arguments it is clear that a species of plants that has proven presence in the bank toe-region of channels in temperate regions, inherently carries with it the adaptive attributes that will ensure the continuation of existence as a species in its preferred habitat. One must be reminded that this (vegetation) is the only 'living' component of the three principal components of the fluvial ecosystem (1.2.3). As such it has developed its phenotype from a long process of development of adaptive attributes through evolution. The simplest message it can carry is that 'if it is to survive then its habitat should be intact ; to make the habitat intact it has to make its own contribution '. In the case of this plant it contributes to the stability of the bank soil by a host of possible parameters of ecological and geomorphological significance as discussed above.

7.4 Natural re-vegetation as a non-structural means of bank protection;

In Chapter 5 the experiment on natural re-vegetation of a denuded bank addresses a fundamental question of scientific and applied interest. *Are there possibilities of a self-balancing natural fluvial ecosystem* (see objectives set in 1.2.3)?

The prime objective is the maintenance of geomorphological aspects of slope stability, soil characteristics and channel stability. The expectation is that ecological aspects of secondary succession, plant demography and competition will ensure the geomorphic stability. Smith (1976) states that the remarkable stability of channels in Alexandra Valley, Canada, over the last 2500 years is due to the bank vegetation. Wolman and Leopold (1957) discuss 17 rivers around the world where channel

migration can vary between 0 and 750m y⁻¹. Obviously some natural fluvial ecosystems are more stable than others due to different reasons. But Smith's reasoning on channel stability due to bank vegetation is logical and in keeping with his field data.

i) *How successful is the process of natural re-vegetation on a devegetated river bank ?*

a) The measure of success will be the reduction in erosion or erodibility of the exposed soil. There is a high reduction of erodibility of the soil as discussed in 5.5.2a . with the initial stages of establishment of ground cover species that initially colonise a disturbed / devegetated bank slope.

b) Within 18 months the naturally re-vegetated plots reach the low erosion rates of naturally existing mature bank vegetation (5.5.2a).

c) The process of natural re-vegetation in the toe region is almost complete within one season of growth. The erosion rates (see 5.5.2b) are decreased to the same levels as a long-term naturally vegetated bank.

d) The time period for returning to normality is between one to two seasons of growth, on the proviso that there are no summer floods of magnitudes that are highly erosive.

e) On the whole natural re-vegetation of a devegetated bank is an efficient process of negation of erosion of banks.

f) The measure of success in negating erosion as achieved with the initial process of natural re-vegetation is not due to the establishment of any of the major spatial colonisers present in the long-established natural vegetation along this stretch of the river. As discussed with the 'species establishment' in 5.5, there were hardly any *Urtica dioica* or *Epilobium hirsutum* established up to the second summer of re-vegetation. This means that the first colonisers in the process of secondary colonisation of a de-vegetated river bank are not those that would be the major constituents in its final climax community. But these colonisers are highly efficient in the process of establishment on such a 'fragile' ecosystem as a bare bank of a river which, within one summer of establishment, would subject them to such tests of 'fitness' as four months of continuous winter submergence and highly erosive discharges. If the hypothesis that is tested is whether the initial colonisers have the capability to conserve the bank soil not only in arresting

ongoing erosion at the time of colonisation but their ability conserve their habitat (the bank soil) under a long-term flood, then these species have proved it beyond any doubt.

A factor of ecological importance together with long-term bank stability is that with time, the phenomenon of reversal of the relative magnitudes of rates of erosion within the bank profile occurs. In essence, the upper bank which initially (eg. January, February, March 1987) showed a much higher rate of erosion when compared with the lower bank, indicates a lower rate of erosion from July 1987. This is interesting because it involves both temporal and spatial aspects aligned to short-term succession of colonisers. The causative factor is the new flush of re-vegetation growth of the summer of 1987 (see Appendix 7a-c).

If this phenomenon arises out of ecological aspects such as competitive exclusion of toe-region plants by better competitors such as *U. dioica* up the bank, which would either shade out the toe-region vegetation or cause some other factor such as allelopathy, then the long-term stability of the bank may be at risk due to undercutting (see discussion in 3.4.2f).

But, long-term stability may be more an outcome of the climax ecosystem that will prevail after decades of successive stages of a disturbed soil. This has been proven in dryland slopes and in old field succession by numerous authors.

A question may arise as to why efficient cohorts of species who constitute the pioneers of secondary succession are competed out by later colonisers who in turn will be competed out by the 'climax community' (Odum 1953). There is no simple answer to such questions except to remember that 'nature having healed its own wounds with one set of pioneer species favours their replacement by better competitors on a longer time scale'. That is an essential component of secondary succession.

Other aspects of significant importance :

- i) mulch/ litter cover on devegetated banks helps to reduce the erodibility of them in the first floods consequent to denudation (see 5.4.2a);
- ii) after the wash-out or decay of the mulch cover the erodibility of the exposed soil increases more than that of a bank which had its dead vegetation removed after the application of the herbicide (see 5.4.2a);

7.5 The survey:

The survey was an attempt to identify whether any species-specific characteristics of plants would have a major influence on the three parameters that were used as the quantitative aspects i.e. shear strength, moisture content and root length per unit volume of soil.

It not only proves the validity of the first assumption but also confirms the conclusions on characteristics attributed to certain plots dominated by certain species (eg. Plot 3a dominated by *E. hirsutum* while Plot 5a was dominated by *U. dioica*) in the experiments 1, 2 and 3.

However, the erosion studies in the experiments question the validity of the prominence attributed to shear strength of the banks as a measure of its erodibility under natural vegetation, cultivated grass banks or naturally re-vegetated banks. The main inference that summarises the spectrum of detailed findings is that bank vegetation is an efficient intermediary that negates both corrosion and slumping. It is so efficient that the critical levels of shear strengths expected for maintaining bank stability if they were bare banks, can be considerably lowered if bank vegetation is advocated as a non-structural mode of cheap and efficient bank lining. Such conclusions may lead to practical prescriptions of considerable socio-economic and environmental values conducive to many societies.

7.6. Socio-economic implications

Globally there is considerable potential for non-structural (termed 'soft options' by engineering consultants) lining of canals, streams and rivers. Socio-economically the fundamental aspects are cost-effectiveness and efficiency in bank protection offered by cultivation of appropriate bank vegetation. *Phalaris arundinacea* has been proved to be easy to establish by seeding when the channel flow can be controlled to allow its initial establishment. Natural re-vegetation is an effective measure but as discussed in Chapter 5 may not be as effective as *Phalaris arundinacea*, unless managed/encouraged by man.

The diversity of species (see Ch. 5 and App. 7a to 7c) which show potential as pioneer colonisers is encouraging. This observation of secondary succession may be compared with the traditional species of bank vegetation grown by many agrarian

societies with a dual purpose objective. For example it is common for paddy farmers in Sri Lanka and Bangladesh to grow a range of edible species of vegetation on banks of irrigation canals. Their traditional techniques have stood the test of time for over 2500 years. Every alternate year the farmers dredge the canals and deposit the silt on the banks to enhance its stability and retain the profile. The next step is one of cooperation between the men, women and children in planting cuttings of vegetable species such as *Hydrocotyle sibthorpiodes* (local name *Diya Gotukola*) and cuttings and rhizomes of *Alternanthera rubra* (local name: *Ratu Heen Mukunuwenna*) or *A. sessilis* (local name *Pala Mukunuwenna*; N.B. "Pala" means vegetable). Some seeding of other edible species are concurrently carried out. The direct immediate result is a socially co-operative, economically advantageous, and technically efficient channel maintenance. Within a few weeks of planting the new succulent shoots are nipped for food. The nipping encourages a host of younger shoots to grow within a short period. This is followed by periodic harvesting of the edible young shoots. This practice encourages a limiting 'effective height' of the channel bank vegetation. The perennial effect on the bank is one of mature yet stunted and thick foliar cover that forms an effective bank liner preventing erosion. It is effective in preventing surficial erosion from precipitation as well as corrasion and slumping from increased channel flow. Another significant contribution by semi-aquatic/amphibious and lower bank coloniser species such as *Bacopa monnieri* (local name *Lunuwila*; about the most sour laxative the author endured as a child; said to 'purify the blood stream'), and various *Cryptocoryne* spp. (eg. *C. beckettii*, *C. parva*, *C. lutea*, *C. petchii*, *C. thwaitesii* and *C. willisii*) is in traditional/indigenous medicines. The overall result of such practices is a cohesive social effort with sustainable productivity at a local/regional level.

The applied implications of non-structural, traditional channel revetment techniques at a national level are considerable. The paucity of scientific explanation for such techniques prevents their recommendations as mentioned in the introduction. The need to 'develop' the irrigation and river systems in the 'Southern hemisphere' in such haste, as currently advocated, is highly controversial. This is in contrast to the Rio conventions on "Agenda 21 and sustainable development". Yet, scientific validation of

non-structural bank linings is essential to assist the international consultants to recommend them. Further confirmation of work and results similar to this study are essential from within the tropical river and irrigation development regions. "One swallow does not make a summer". It is hoped that this work gains some attention from the international Development Aid community as a *"pump priming" exercise for funding* similar projects in the near future. Such studies may help some poor nations to (a) save a potentially considerable debt burden, (b) create eco-positive irrigation solutions, and (c) enjoy a low management input yet form a cohesive social morale and derive high efficiency from canals.

In the technically advanced 'Northern hemisphere', the need to apply 'soft options' in national river development schemes is already understood. Work in restoration of previously straightened and channelised rivers are in progress over the last two decades (Brookes, 1987, & 1988). In describing the application of the European experience of 15 restoration projects in Denmark and Britain, to two projects, Brookes (1990) evaluates the techniques used in achieving vegetational diversity. While no mention is made of traditional techniques or socio-economic implications the underlying theme of addressing technological problems through eco-positive solutions is apparent. Petts (1984) discusses the perspectives for ecological management of the river systems. The importance of aquatic and riparian vegetation, and channel geomorphology are discussed with an extensive bibliography (36 pages). The need to base decisions on river developments upon a range of social, economic and political criteria is expressed.

Standards set in advanced countries are applied in the developing countries with a 'time lag' factor. Some of the most publicised examples are instances of withdrawal of 'dangerous' medicines and agricultural applications such as herbicides and insecticides with time lags of over decades. In essence, the aid donor agencies must realise that the structural techniques of bank protection advocated to the poor countries as part of the 'development programme' is in fact an obsolete technique in the developed countries that initially formulated it. Further research such as this study on non-structural techniques may help to retain a much needed social cohesiveness in an otherwise disintegrating

society. The economic benefits at personal or regional and national level may inevitably follow.

7.7 Future directions

Comments on necessary future research work have been made throughout the thesis as and when the discussions led to such future directions. There is a need to address the role of bank vegetation in terms of two fundamental areas of research. They both arise due to the lack of consistency in correlations between root density and shear strength of the bank. The two areas are:

i. phyllospheric studies (the term phyllospheric is preferred to shoots because it implies the physical spatial concept as opposed to the individual shoots of a plant);

This study identifies effect of the above ground plant as a defined physical entity within the operative fluvial system; The same approach is identified in recent works of Kouwen (1988) and Masterman and Thorne (1992) Yet they are directed at building predictive models as attempts to optimise the classic models of Manning and Darcy Weisbach. This approach may suffice for purposes of identifying influences of bank vegetation as a factor to be incorporated in terms of channel 'roughness factor'.

The results of this study while rejecting the effects of root density in terms of bank shear strength identifies the critical role of bank vegetation as a bank protector. This aspect is in contrast to that of roughness factor. The protective aspects deal with the 'positive overview' of physical functional role of the vegetation as opposed to the 'negative overview' of flow retardance. Therefore future research will have to address a spectrum of research projects on how the bank phyllosphere ensures stability of the bank through morphological effects on ground cover of the channel bank. This will have to be extended to identify seasonal variations as well as regional variations around the globe.

The first proposal is to study the ground cover offered by young pioneer colonisers of an eroding or newly bare bank. The reader is referred to standard descriptive books in Botany such as Keble Martin (1969) to appreciate the diversity of leaf forms in species within the British Isles. In this study the rates of erosion under an essentially filiform/ linear leaf species (*P. arundinacea*; see Ch. 4) has been studied. The observation of a host of morphologically contrasting species of pioneer colonisers (Ch.

5) and their short term effectiveness in arresting erosion needs to be researched further. The essential idea is to quantify (a) leaf area (b) leaf orientation and (c) ground cover offered from seedling to maturity. It is appreciated that at the latter stages of growth complications may arise on quantification. For example overlap of leaves may present problems of effective leaf area in terms of effective ground cover. This may be overcome through efficient project design and identification of technique/s for analysis. The fundamental aim should be to identify whether leaf size and orientation at different stages of growth offer different ground cover to the bank. The final aim should be to test the hypothesis that *certain pioneer colonisers of eroding banks have species specific physical attributes within the phyllosphere that may be beneficial to prevent bank erosion.*

The second proposal is to identify the species specific characteristics of bank vegetation in their orientation on the banks (a) during summer floods i.e. in full foliage and (b) in winter during senility and defoliated periods. Recent accentuation on studies of 'effective height' (Kouwen, 1988; Masterman and Thorne, 1992) of bank vegetation during flood regimes are an appreciation of the fact that previous assignments on Manning's values are too high when compared to the effective orientation height of the vegetation on the banks during floods.

In this study a further development is identified. While the concept of 'effective heights' of bank vegetation under inundation is appreciated, there is a need to identify such orientations for different species of bank vegetation in (a) summer , and (b) in winter. Kouwen and Li (1980) identify 'stiffness' of vegetation as a key factor in orientation and quantify as a product of "density, elasticity and bendiness of vegetation". Field valuation was carried out for grasses from the height of the grass or dropping a board to test its stiffness directly. Perhaps a comprehensive data base for different species should be created with a refined technique. Furthermore the decay of shoots under long-term floods in winter must be addressed. As this study confirms the role of the shoot system as that of negation of bank erosion, decay of the shoot system or the wintry vestiges of it, is a critical factor of significance in bank erodibility. The final aim should be that of predictability of bank instability under a given vegetation and a given flow regime.

The author is of the view that since (a) the root effects (through shear strength and hence Mohr Coulomb) are discounted, and (b) hydraulic models of the predictive flow category may be inappropriate in explaining bank erosion, an initial and necessary phase of "process oriented research " should be addressed. A study on shoot orientation as a species-specific character before and after an inundation must be a first step.

The third proposal is a long term project on the theme of stability of ecosystems. It is an attempt to understand the establishment of populations in communities. The main aspect to be addressed is the extent to which an existing community is vulnerable to invasion by other species. This can be specifically aimed at an understanding of the effects of repeated disturbances (by high flows that may uproot some species in the habitat) on the invasability of communities and habitats. Ideally it should be a means of testing available theoretical models on population dynamics within an ecosystem that is subject to regular disturbance. There is a paucity of literature on this area of applicable relevance in fluvial morphology and river management.

On the basis of the anchorage offered by live roots to winter bank foliage, research needs to be directed at :

(i) direct physical effects of anchorage; It necessitates an experiment by which erosion may be observed in a river bank where:

a) one set of treatments has dead foliage lying on the surface with either an artificial anchoring source for retention of the dead foliage on the banks while storm flows are repeated in the channel or a more natural situation as experienced by the Normal vegetation plots (3a, 3b, 6a, 6b, 14a, & 14b) where in winter, the dead foliage is anchored to the bank by a root system which is active as evidenced by the presence of live roots;

b) another set of treatments has dead foliage lying on the surface as cover litter with no anchoring;

c) thirdly sets of similar foliage to (a & b above) should be anchored to the soil via either pieces of elastic of known tensile properties, or a series of 'dead weights';

The experimental flow regimes in the channel should be variable and quantifiable. It is not intended to present further details and analytical techniques for the

results. Two crucial aspects can be addressed, viz. (1) is anchorage of the shoot system necessary to prevent erosion of the bank? (2) can critical values of anchorage or tensile values be identified for the stability of a given foliage under varying discharges. The possibility of developing mathematical models is identified.

(ii) *on live/dead root turnover as a species specific attribute.* This may indicate the survivability or suitability of a bank vegetation species in negating erosion. There is a need to re-address the effects of roots in terms of soil cohesion. The roles of (a) root exudates, (b) root hairs in rootlets in cohesion between soil particles and the roots has to be studied in laboratory-scale experiments, so that an understanding of these relationships are made in terms of individual plant species. Any current theories on root contribution to soil cohesion (not necessarily shear strength) will have to be addressed

On a longer time scale as appropriate to understand secondary succession, an experiment should be conducted on an intensive and extensive scale, of colonisation of a bare bank on the temporal and spatial aspects of species turnover and their effects on erosion. Plant demography and species interactions, should be accentuated in such a study.

It may be useful to understand the process of 'basal end point control' under different types of vegetation. The topic of meander formation could be addressed through a survey of the presence or absence of vegetation at positions of such meander initiation.

As a future research project, this should throw light on many aspects of theoretical and applicable interests such as :

- a) stress tolerance (Grime, 1979) by roots of submerged plants and their 'fitness' (c.f. Silvertown, 1987) which would reflect the evolutionary attributes the species of plants has in relation to survival in the given fluvial system;
- b) if cohesion with the soil particles around the roots under submergence is attributed to the root exudates and mucilages there is reason to believe that bank soil stability arises from such a process intrinsic to the roots of a given species of plants;
- c) if there is no such relationship between the roots and the soil then the non-erodibility of the bank has to be attributed to either a phenomenon such as specially shaped roots that

prevent soil erosion (Turmanina, 1965; Vanicek, 1973), or the intermediary role of the phyllosphere as a physical barrier between the motive fluvial force and the bank; However, it has to be remembered that floods occur in the temperate countries during winter when the phyllosphere is weaker than during the summer. The deciduous bank vegetation is a skeletal pattern of dead stems. But, the dead and decaying leaves that have fallen to the bank surface may form a layer of detritus that prevents the process of erosion.

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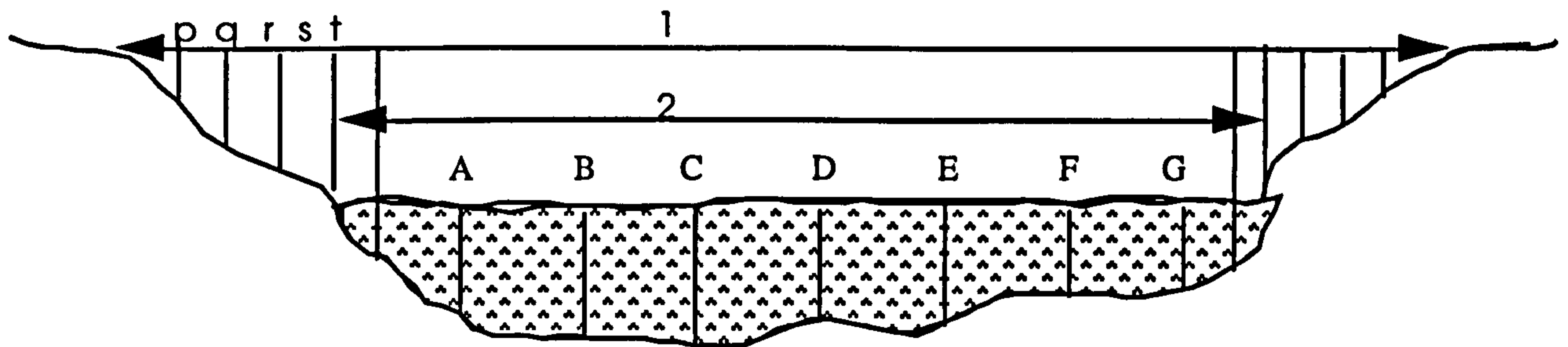
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Appendix 1: Cross section of River Ouzel at the experimental site

1 = Breadth across river from apex of one bank to the opposite
= 11.0metres (approx); It varies within a range of 0.75m
along the length of the experimental area;
2 = Breadth across the water at ambient water level(i.e. 50cm at
toe-region) = 7.45metres (approx); It varies within a range of
0.6m. along the experimental area;

Depth of water at:

A = 0.8m;
B = 1.2m;
C = 1.25m;
D = 1.1m
E = 1.2m;
F = 0.85m;
G = 0.7m;



Cross section across Plots 3a and 3b (as measured in August 1986)

Vertical height from horizontal line across opposite banks indicated varying depths to the bank surface. The vertical lines shown (at p, q, r, s, v, w, x, and y) are points of measurements which were above the erosion pin positions on the bank. For example, p, q, r, s are at 2.0, 1.5, 1.0, and 0.5m from the bank-toe at t (t is approximately 0.5m away from s ; Comparisons with the original plans of the channel construction supplied by Anglian Water show that there has been a continuous process of erosion at this level which can be attributed to undercutting at ambient flow and high flows over the years).

Heights at: p = 0.5m, q = 0.7m, r = 0.8m and s = 1.0m (approximately);

N.B. as there was a variation for the four profiles measured for the river cross section at each position the above represents an average view and profile across the channel.

**TEXT BOUND
INTO
THE SPINE**

Appendix 2 Flow data

Monthth/Year	Period(days)	MeanFlow(l/s)	Std. Error	MinimumFlow	Max.Flow
Ju-Au86	60	876.42	28.96	578	1700
Au-Se86	32	856.41	67.93	567	2200
Se-Oc86	31	791.39	66.82	567	2325
Oc-De86	77	2383.62	187.02	611	7560
De86-Ja87	16	5061.31	554.18	1700	8820
Ja-Fe87	45	1769.55	67.16	1280	3450
Fe-Ma87	28	2028.00	161.16	1050	4140
Ma-Ap87	36	3143.61	403.51	1130	11610
Ap-My87	24	1043.50	32.15	887	1500
My-Ju87	28	1841.71	207.36	813	4450
Ju-Jy87	28	1924.04	340.61	741	8360
Jy-Au87	31	1261.03	84.50	805	2910
Au-Se87	32	953.22	58.13	118	1850
Se-De87	84	4355.77	472.08	680	22510
De87-Ja88	42	3210.02	268.41	1620	10363
Ja-Fe88	34	7027.65	910.90	2010	21683
*Se87-Fe88	160	4622.79	337.35	680	22510
Fe-Ap88	48	2626.45	245.68	1460	9005
Ap-My88	35	1423.34	59.43	1080	2780
My-Ju88	31	1150.00	46.41	859	2200
Ju-Jy88	30	1395.40	121.61	716	3500

Channel flow data as presented above represent :

- the period between measurements;
- the number of days between erosion measurements; N.B. Sep.87 to Feb 88 as the long flood period for which cumulative figures only are available for the lower banks;
- the mean flow (l/s), and (d) its standard error;
- maximum flow (l/s) during the erosion period;
- minimum flow (l/s) during the erosion period.

Appendix 3a : Summary of Mean erosion data (mm/d) for Bare treatment

Month/Year	Days Eroded	Mean/d(mm)	S.E/d (mm)
Ju-Au 86	60	0.1219	0.0458
Au-Se 86	31	0.7814	0.1876
Se-Oc 86	30	0.3068	0.0839
Oc-De 86	77	0.2421	0.0445
De86-Ja87	16	2.2176	0.3385
Ja-Fe 87	44	0.5093	0.0826
Fe-Ma 87	27	1.0034	0.1545
Ma-Ap 87	36	0.7594	0.0680
Ap-My 87	24	0.2825	0.0311
My-Ju 87	28	0.2662	0.0173
Ju-Jy 87	28	0.3967	0.0471
Jy-Au 87	31	0.2151	0.0075
Au-Se 87	31	0.2389	0.0115
Se-De 87	84/160	1.3000	0.0588
De87-Ja88	42/160	1.2489	0.0490
Ja-Fe 88	34/160	1.5201	0.0725
*Se87-Fe88	160	0.4323	0.0268
Fe-Ap 88	47	0.5339	0.0211
Ap-My 88	35	0.1665	0.0122
My-Ju 88	31	0.1692	0.0096
Ju-Jy 88	30	0.1206	0.0079

Appendix 3b : Summary of Mean erosion data (mm/d) for Natural vegetation treatment

Month/Year	Days Eroded	Mean/d(mm)	S.E./d(mm)
Ju-Au 86	60	0.0000	0.0000
Au-Se 86	31	0.0149	0.0127
Se-Oc 86	30	0.0000	0.0000
Oc-De 86	77	0.0293	0.0137
De86-Ja87	16	0.1875	0.0412
Ja-Fe 87	44	0.0369	0.0153
Fe-Ma 87	27	0.0833	0.0238
Ma-Ap 87	36	0.0753	0.0084
Ap-My 87	24	0.0361	0.0044
My-Ju 87	28	0.0766	0.0036
Ju-Jy 87	28	0.0858	0.0038
Jy-Au 87	31	0.0686	0.0035
Au-Se 87	31	0.1274	0.0067
Se-De 87	84/160	0.0630	0.0054
De87-Ja88	42/160	0.0534	0.0049
Ja-Fe 88	34/160	0.2579	0.0109
*Se87-Fe88	160	0.0362	0.0187
Fe-Ap 88	47	0.0587	0.0034
Ap-My 88	35	0.0260	0.0034
My-Ju 88	31	0.0329	0.0042
Ju-Jy 88	30	0.0306	0.0033

Appendix 3c :Summary of Mean erosion data (mm/d) for *Phalaris arundinacea* treatment

Month/Year	Days Eroded	Mean/d (mm)	S.E./d(mm)
Ju-Au 86	60	0.2525	0.0695
Au-Se 86	31	0.4886	0.1325
Se-Oc 86	30	0.2549	0.0706
Oc-De 86	77	0.2116	0.0449
De86-Ja87	16	1.2431	0.2805
Ja-Fe 87	44	0.4715	0.0813
Fe-Ma 87	27	1.0999	0.2063
Ma-Ap 87	36	0.3887	0.0431
Ap-My 87	24	0.2254	0.0181
My-Ju 87	28	0.2636	0.0237
Ju-Jy 87	28	0.2963	0.0165
Jy-Au 87	31	0.1590	0.0089
Au-Se 87	31	0.1336	0.0086
Se-De 87	84/160	0.0947	0.0119
De87-Ja88	42/160	0.1037	0.0079
Ja-Fe 88	34/160	0.2156	0.0064
*Se87-Fe88	160	0.0416	0.0054
Fe-Ap 88	47	0.0621	0.0048
Ap-My 88	35	0.0570	0.0051
My-Ju 88	31	0.0503	0.0054
Ju-Jy 88	30	0.0381	0.0048

Appendix 3d : Summary of Mean erosion data (mm/d) for Natural re-vegetation treatment

Month/Year	Days Eroded	Mean/d(mm)	S.E./d(mm)
Ju-Au 86	60	0.0256	0.0167
Au-Se 86	31	0.0783	0.0262
Se-Oc 86	30	0.1615	0.1051
Oc-De 86	77	0.2172	0.0686
De86-Ja87	16	1.1551	0.3793
Ja-Fe 87	44	0.5951	0.0989
Fe-Ma 87	27	1.4534	0.1437
Ma-Ap 87	36	1.1871	0.1086
Ap-My 87	24	0.2522	0.0201
My-Ju 87	28	0.2509	0.0182
Ju-Jy 87	28	0.2435	0.0205
Jy-Au 87	31	0.1598	0.0098
Au-Se 87	31	0.1526	0.0084
Se-De 87	84/160	0.1653	0.0090
De87-Ja88	42/160	0.1300	0.0116
Ja-Fe 88	34/160	0.3444	0.0085
*Se87-Fe88	160	0.0657	0.0079
Fe-Ap 88	47	0.0899	0.0049
Ap-My 88	35	0.0413	0.0034
My-Ju 88	31	0.0423	0.0040
Ju-Jy 88	30	0.0316	0.0032

Appendix 4a : Summary of Mean erosion data (mm/d) for the "Upper banks" of all four treatments in the experiments

Bare U = Bare soil plots;

Normal = Natural vegetation plots;

P. arun = *Phalaris arundinacea* plots;

Re-veg = Natural re-vegetation plots;

U = Upper bank;

S.E./d = Standard error;

Mth/Year	Bare/U	S.E./d(B)	Normal/U	S.E./D(N)	P. arun/U	S.E./D(P)	Re-veg/U	S.E./D(R)
Ju-Au 86	0.1829	0.0666	0.0000	0.0000	0.3787	0.0980	0.0384	0.0248
Au-Se 86	1.1425	0.1353	0.0188	0.0097	0.6756	0.0989	0.0968	0.0193
Se-Oc 86	0.4602	0.1063	0.0000	0.0000	0.3713	0.0907	0.2422	0.1427
Oc-De 86	0.3265	0.0608	0.0051	0.0035	0.2695	0.0633	0.2839	0.1006
De86-Ja87	2.8889	0.4396	0.0556	0.0274	1.6632	0.3924	1.6510	0.5514
Ja-Fe 87	0.6181	0.1086	0.0299	0.0141	0.6481	0.1036	0.7967	0.1338
Fe-Ma 87	1.2418	0.1585	0.0577	0.0197	1.4772	0.2150	1.8076	0.1230
Ma-Apr 87	0.8183	0.0785	0.0367	0.0097	0.3979	0.0497	1.5098	0.1254
Apr-May 87	0.3132	0.0359	0.0167	0.0051	0.2543	0.0209	0.2844	0.0232
May-Ju 87	0.2106	0.0200	0.0157	0.0042	0.2622	0.0274	0.2208	0.0211
Ju-Jy 87	0.3566	0.0544	0.0154	0.0044	0.2350	0.0190	0.1970	0.0237
Jy-Au 87	0.1769	0.0087	0.0145	0.0041	0.1395	0.0103	0.1126	0.0113
Au-Se 87	0.1953	0.0133	0.0626	0.0077	0.1142	0.0100	0.1078	0.0097
Se-De 87	1.3000	0.0588	0.0630	0.0054	0.0947	0.0119	0.1653	0.0090
De87-Ja88	1.2489	0.0490	0.0534	0.0049	0.1037	0.0079	0.1300	0.0116
Ja-Fe 88	0.4323	0.0268	0.0362	0.0187	0.0416	0.0054	0.0657	0.0079
*Se87-Fe88	0.4271	0.0157	0.0225	0.0014	0.0328	0.0023	0.0487	0.0024
Fe-Apr 88	0.4860	0.0244	0.0386	0.0039	0.0491	0.0056	0.0790	0.0056
Apr-May 88	0.1633	0.0138	0.0234	0.0038	0.0492	0.0057	0.0333	0.0039
May-Ju 88	0.1617	0.0107	0.0311	0.0047	0.0527	0.0060	0.0380	0.0045
Ju-Jy 88	0.1119	0.0087	0.0199	0.0037	0.0306	0.0054	0.0222	0.0036

Appendix 4b : Summary of Mean erosion data (mm/d) for the "Lower banks" of all four treatments in the experiments

Bare U = Bare soil plots;
 Normal = Natural vegetation plots;
 P. arun = *Phalaris arundinacea* plots;
 Re-veg = Natural re-vegetation plots;
 L = Lower bank (upto 0.75m from bank-toe);
 S.E./d = Standard error;

Mth/Year	Bare/L	S.E./d(B)	Normal/L	S.E./D(N)	P. arun/L	S.E./D(P)	Re-veg/L	S.E./D(R)
Ju-Au 86	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Au-Se 86	0.0591	0.0285	0.0072	0.0072	0.1147	0.0313	0.0412	0.0237
Se-Oc 86	0.0000	0.0000	0.0000	0.0000	0.0222	0.0060	0.0000	0.0000
Oc-De 86	0.0634	0.0174	0.0779	0.0385	0.0960	0.0335	0.0837	0.0272
De86-Ja87	0.8750	0.3414	0.4514	0.0814	0.4028	0.1990	0.1632	0.0814
Ja-Fe 87	0.2917	0.1049	0.0505	0.0311	0.1477	0.0914	0.1919	0.0596
Fe-Ma 87	0.5267	0.1390	0.1317	0.0472	0.3663	0.1173	0.7449	0.1950
Ma-Ap 87	0.5827	0.1149	0.1905	0.0315	0.3611	0.0677	0.2269	0.0357
Ap-My 87	0.1905	0.0319	0.0955	0.0302	0.1389	0.0237	0.1558	0.0253
My-Ju 87	0.4328	0.0574	0.2622	0.0204	0.2679	0.0459	0.3410	0.0505
Ju-Jy 87	0.5170	0.0541	0.2951	0.0191	0.4804	0.0700	0.3902	0.0796
Jy-Au 87	0.3295	0.0378	0.2296	0.0282	0.2174	0.0365	0.3011	0.0432
Au-Se 87	0.3694	0.0438	0.3126	0.0253	0.1920	0.0212	0.2873	0.0181
Se-De 87	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
De87-Ja88	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ja-Fe 88	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
*Se87-Fe88	0.4790	0.0357	0.1557	0.0245	0.1186	0.0170	0.2176	0.0273
Fe-Ap 88	0.6778	0.0998	0.1162	0.0176	0.1002	0.0099	0.1226	0.0103
Ap-My 88	0.1762	0.0216	0.0333	0.0069	0.0789	0.0106	0.0657	0.0118
My-Ju 88	0.2212	0.0351	0.0488	0.0173	0.0722	0.0188	0.0574	0.0132
Ju-Jy 88	0.1468	0.0176	0.0618	0.0128	0.0595	0.0114	0.0571	0.0094

Appendix 5a : Mean Shear strength and Moisture content values for August 1986

	P1/ %MC	P1/ kPa	P2/ %MC	P2/kPa	P3/ %MC	P3/kPa	P5/ %MC	P5/kPa
Level 4	27.42 (0.71)	59.0 (5.00)	26.19 (1.68)	98.7 (5.45)	26.29 (3.88)	>120.0	33.34 (0.71)	>120.0
Level 4	21.54 (2.63)	21.6 (0.88)	13.29 (1.52)	133.7	25.77 (0.32)	>120.0	26.73 (1.27)	>120.0
Level 4	16.49 (1.76)	>120	29.06 (2.32)	19.4 (0.60)	22.08 (0.98)	>120.0	33.54 (0.92)	>120.0
Level 4	21.59 (1.63)	37.3 (1.33)	28.99 (2.43)	31.5 (1.50)	19.95 (1.07)	>120.0	16.07 (0.26)	>120.0
Level 3	24.75 (2.82)	8.7 (1.20)	23.29 (2.02)	11.4 (1.53)	24.11 (1.57)	>120.0	29.68 (0.36)	>120.0
Level 3	30.57 (0.44)	10.0 (0.00)	20.99 (2.25)	10.7 (0.33)	26.34 (0.73)	>120.0	32.97 (1.63)	78.0 (6.00)
Level 3	28.00 (1.22)	11.3 (0.66)	36.14 (2.07)	10.7 (1.33)	14.45 (0.67)	106.0 (4.0)	19.19 (2.05)	92.0 (6.00)
Level 3	33.89 (1.97)	10.7 (0.66)	42.27 (0.95)	19.7 (2.78)	15.20 (1.70)	102.0 (1.0)	46.97 (1.34)	86.7 (3.33)
Level 2	26.69 (1.11)	7.5 (0.50)	40.49 (0.57)	21.5 (1.50)	29.16 (11.23)	39.3 (4.05)	24.52 (1.59)	40.4 (5.50)
Level 2	20.63 (0.02)	7.5 (0.50)	38.27 (1.04)	10.7 (1.33)	30.57 (14.06)	47.1 (1.0)	22.39 (1.47)	39.7 (3.32)
Level 2	28.03 (2.00)	9.7 (0.67)	36.14 (0.12)	10.7 (1.33)	28.54 (1.02)	37.3 (1.856)	32.87 (2.29)	41.4 (7.00)
Level 2	31.93 (2.05)	7.7 (0.33)	42.27 (1.07)	9.4 (0.40)	42.67 (2.31)	19.6 (1.20)	43.77 (2.19)	39.4 (2.90)
Level 1	50.82 (6.11)	11.7 (1.45)	68.52 (0.60)	10.7 (0.667)	37.98 (1.07)	36.3 (2.72)	47.19 (1.7)	20.5 (2.5)
Level 1	50.17 (9.25)	11.7 (0.88)	55.79 (0.51)	7.5 (0.50)	42.32 (0.82)	9.8 (3.83)	40.64 (0.88)	18.4 (1.5)
Level 1	55.74 (1.37)	11.7 (1.45)	60.20 (2.08)	9.4 (0.74)	89.76 (2.84)	9.8 (2.17)	68.69 (5.62)	17.5 (0.5)
Level 1	42.95 (2.61)	9.8 (0.25)	50.78 (3.77)	18.7 (1.33)	54.57 (2.38)	19.6 (0.5)	48.38 (5.99)	12.7 (1.76)

P1 = Plot 1a (Bare soil);

P2= Plot 2a (*Phalaris arundinacea* seeds sown);

P3 = Plot 3a (Natural vegetation dominated by *E. hirsutum*);

P5 = Plot 5a (Natural vegetation dominated by *U. dioica*)

% MC = percentage moisture contentent; kPa = Shear strength (kPa);

Levels 1 - 4 are as described in Fig. 2.4.

Figures within brackets are Standard errors for the position. Number of samples were 2 each for moisture content and between 3 to five for shear strength.

(N.B. for August 1986 and February 1987 measurements were carried out on 4 positions at each level while subsequent measurements were limited to 3 positions)

**Appendix 5b : Mean Shear strength and Moisture content values for
February 1987**

	P1/ %MC	P1/ kPa	P2/ %MC	P2/kPa	P3/%MC	P3/kPa	P5/ %MC	P5/kPa
Level 4	29.30 (0.89)	52.0 (8.00)	31.75 (0.27)	70.0 (8.00)	34.60 (0.88)	106.0 (10.39)	31.1 (0.69)	84.0 (1.00)
Level 4	22.30 (0.79)	52.0 (1.764)	33.17 (0.34)	35.0 (1.00)	22.70 (2.62)	92.0 (3.05)	36.9 (1.120)	55.0 (5.13)
Level 4	23.70 (0.68)	61.0 (2.00)	27.12 (1.18)	67.0 (1.00)	33.60 (3.51)	100.0 (9.86)	40.5 (0.84)	98.0 (4.00)
Level 4	30.80 (2.07)	80.0 (0.00)	30.92 (0.49)	88.0 (2.00)	54.80 (3.52)	56.5 (0.50)	43.5 (1.43)	63.0 (16.90)
Level 3	35.90 4.18)	13.0 (1.00)	21.74 (0.90)	20.0 (0.00)	38.90 (3.93)	80.0 (0.00)	27.3 (1.03)	42.0 (0.00)
Level 3	28.16 (1.86)	45.0 (0.00)	32.80 (0.88)	10.0 (0.00)	20.07 (1.46)	86.0 (4.00)	31.6 (1.61)	36.0 (2.00)
Level 3	38.18 (3.20)	12.0 (4.00)	34.52 (1.46)	12.0 (0.00)	42.34 (8.69)	42.0 (3.05)	32.5 (1.03)	30.0 (0.00)
Level 3	38.33 (1.51)	16.0 (0.00)	42.91 (0.51)	25.0 (1.00)	48.40 (1.17)	64.0 (2.00)	44.9 (0.92)	62.0 (2.00)
Level 2	43.50 (1.34)	10.0 (2.00)	47.31 (1.49)	22.0 (2.00)	48.10 (1.95)	15.2 (1.100)	55.4 (1.49)	14.0 (2.00)
Level 2	43.40 (1,34)	8.0 (0.00)	49.63 (1.74)	12.2 (1.29)	45.12 (0.06)	7.0 (0.57)	52.0 (3.03)	12.0 (1.15)
Level 2	43.90 4.06)	7.0 (1.50)	49.60 (0.18)	10.0 (0.00)	45.50 (1.240)	9.2 (0.47)	57.1 (0.93)	8.0 (0.00)
Level 2	45.27 (1.75)	5.0 (0.00)	45.70 (1.88)	16.1 (1.15)	41.90 (1.67)	16.0 (1.15)	61.1 (1.94)	8.0 (0.00)
Level 1	111.70 (2.07)	5.2 (0.75)	69.00 (0.27)	26.0 (1.15)	98.40 (1.80)	17.0 (1.00)	40.3 (0.72)	8.2 (0.85)
Level 1	57.70 (1.01)	25.0 (5.00)	81.10 (0.34)	11.0 (1.00)	62.50 (4.95)	9.0 (0.00)	90.3 (8.04)	13.1 (3.25)
Level 1	62.50 (2.20)	16.0 (2.00)	70.10 (1.13)	19.0 (1.00)	115.30 (14.4)	16.2 (1.93)	57.5 (0.58)	12.0 (0.00)
Level 1	87.50 (2.30)	11.0 (3.00)	81.20 (0.99)	7.2 (0.37)	57.35 (2.74)	13.2 (2.86)	65.1 (2.94)	13.5 (1.89)

Appendix 5c : Mean Shear strength and Moisture content values for August 1987

	P1/ %MC	P1/ kPa	P2/ %MC	P2/kPa	P3/%MC	P3/kPa	P5/ %MC	P5/kPa
Level 4	26.1 (1.39)	56.00 (2.00)	18.24 (0.84)	88.00 (2.00)	20.07 (2.66)	80.66 (6.66)	27.86 (2.92)	81.33 (3.52)
Level 4	29.0 (1.08)	70.00 (9.45)	13.64 (2.08)	80.00 (7.21)	22.24 (2.82)	83.33 (3.52)	28.12 (2.92)	86.33 (4.80)
Level 4	29.1 (2.11)	56.00 (7.02)	*	*	25.80 (2.88)	94.00 (4.00)	35.62 (4.66)	83.50 (3.50)
Level 3	26.4 (2.24)	40.50 (7.41)	28.40 (1.39)	51.00 (1.00)	28.49 (3.79)	45.33 (1.76)	30.10 (7.400)	48.66 (3.52)
Level 3	11.7 (0.72)	48.00 (4.00)	20.30 (1.68)	54.00 (3.05)	29.54 (5.92)	41.00 (1.00)	24.85 (2.00)	52.33 (3.84)
Level 3	18.6 (1.18)	45.33 (1.76)	27.90 (1.65)	45.33 (1.76)	29.90 (2.09)	40.33 (2.18)	29.31 (4.55)	51.50 (1.00)
Level 2	32.1 (2.01)	20.00 (2.000)	28.77 (1.09)	46.00 (0.00)	51.02 (0.35)	16.66 (1.76)	58.84 (2.50)	15.33 (7.33)
Level 2	28.7 (2.12)	18.00 (1.15)	33.75 (1.90)	30.00 (2.00)	39.94 (3.09)	18.66 (1.33)	53.90 (3.54)	15.33 (3.52)
Level 2	*	*	39.79 (1.17)	36.00 (2.00)	46.50 (2.79)	19.33 (1.76)	49.60 (2.75)	17.50 (2.63)
Level 1	43.8 (7.22)	24.00 (3.05)	76.16 (4.58)	24.00 (3.05)	73.40 (2.59)	12.66 (1.76)	102.1 (4.13)	9.66 (3.18)
Level 1	66.2 (3.44)	18.25 (1.31)	57.41 (5.35)	24.00 (2.00)	60.60 (1.59)	14.66 (0.66)	75.50 (0.90)	14.50 (1.50)
Level 1	79.7 (9.00)	18.50 (2.50)	40.61 (3.42)	20.00 (1.15)	67.51 (12.50)	16.00 (2.00)	70.60 (0.26)	14.50 (1.50)

Appendix 6a															
Mean data for 1988 of % Moisture content, Shear strength (kPa) and total root length per unit volume of soil (L cm); S.E= Standar error;															
Plot 1a /Level 1 / February				Plot 1a /Level 2 / February				Plot 1a /Level 3 / February				Plot 1a /Level 4 / February			
% M C	S.E	kPa	S.E	L(cm)	% M C	S.E	kPa	L(cm)	% M C	S.E	kPa	L(cm)	% M C	S.E	kPa
54.24	0.98	17.33	3.93	1.57	24.04	0.97	14	2	18.32	2.11	41.33	0.667	5.5	25.79	1.06
59.26	1.25	14	2	2.35	11.92	1.01	14.33	2.082	23.75	1.325	20.33	1.528	0	33.29	1.75
72.53	4.2	14.33	1.202	12.57										23.36	0.45
Plot 1a /Level 1 /May				Plot 1a /Level 2 / May				Plot 1a /Level 3 / May				Plot 1a /Level 4 /May			
% M C		kPa		L(cm)	% M C		kPa	L(cm)	% M C		kPa	L(cm)	% M C		kPa
61.36	1.15	20.93	0.882	0	46.27	0.95	24	2	32.41	1.01	40.66	0.882	0	36.42	1.45
58.61	10.95	11.33	2.404	0	56.42	2.49	22.33	0.882	24.12	0.31	33	2.082	3.14	21.43	0.97
82.46	12.965	10.66	1.333	0	52.4	1.98	26.76	1	0			0	24.14	2.05	38
Plot 1a /Level 1 /August				Plot 1a /Level 2 / August				Plot 1a /Level 3 / August				Plot 1a /Level 4 /August			
% M C		kPa		L(cm)	% M C		kPa	L(cm)	% M C		kPa	L(cm)	% M C		kPa
44.91	1.07	19.33	4.372	0	34.17	1.96	21.67	2.728	26.43	1.13	40.5	0.5	5.5	24.71	0.77
62.76	0.71	16.33	1.202	0	29.26	0.96	18.67	4.055	32.19	1.22	40	0	0	27.8	0.23
68.56	2.25	17.33	1.764	0										21.44	0.65
Plot 3a /Level 1 / February				Plot 3a /Level 2 / February				Plot 3a /Level 3 / February				Plot 3a /Level 4 / February			
% M C		kPa		L(cm)	% M C		kPa	L(cm)	% M C		kPa	L(cm)	% M C		kPa
63.12	2.28	10	2	24.35	68.31	2.07	18.66	1.337	58.09	0.37	20	3.055	67.57	54.92	3.28
61.28	4	12.33	0.882	9.43	76.61	3.78	8.66	0.667	64.09	3.16	26.67	1.764	66.78	28.85	1.79
97.25	2.59	8.33	0.882	25.14	73.48	3.22	10.5	0.5	50.89	3.13	24	2	42.43	40.56	1.53
Plot 3a /Level 1 /May				Plot 3a /Level 2 / May				Plot 3a /Level 3 / May				Plot 3a /Level 4 / May			
% M C		kPa		L(cm)	% M C		kPa	L(cm)	% M C		kPa	L(cm)	% M C		kPa
54.37	3.34	12	1.155	32.99	42.28	2.65	14	1.155	44.48	1.74	27.33	0.667	73.86	33.25	2.81
72.03	6.07	12.5	0.5	12.57	47.32	1.4	16.67	1.333	42.37	2.33	39	1	66.79	30.16	1.2
62.21	2.17	11.67	1.202	35.36	44.46	1.04	13.67	0.882	44.02	2.16	27.33	2.404	51.07	30.68	0.62
Plot 3a /Level 1 /August				Plot 3a /Level 2 / August				Plot 3a /Level 3 / August				Plot 3a /Level 4 / August			
% M C		kPa		L(cm)	% M C		kPa	L(cm)	% M C		kPa	L(cm)	% M C		kPa
62.21	2.71	12.67	0.667	36.93	47.54	0.52	21.33	4.667	42.67	2.04	49.33	4.055	67.57	32.47	2.42
66.44	1.89	14.67	1.333	29.07	44.24	1.58	20.33	1.202	40.43	4.02	41.5	1.5	73.07	21.92	9.03
56.82	1.91	15.33	2.404	44	36.71	2.63	18.33	2.728	46.07	6.63	39.33	3.333	91.93	28.47	0.09

Appendix 6b																	
Mean data for 1988 of % Moisture content, Shear strength (kPa) and total root length per unit volume of soil (L cm); S.E= Standar error;																	
Plot 2a /Level 1 / February						Plot 2a /Level 2 / February						Plot2 a /Level 3 / February					
% M C	S.E	kPa	S.E	L(cm)	% M C	S.E	kPa	S.E	L(cm)	% M C	S.E	kPa	S.E	L(cm)	% M C	S.E	L(cm)
56.23	2.58	16	2	357.5	46.7	1.81	16.66	1.333	103.71	36.46	0.4	25.33	4.163	167.35	18.02	0.53	49.33
58.6	0.565	18	2	123.35	47.96	1.72	19	1	62.07	41.16	0.24	30.66	1.764	224.71	28.42	0.4	44.66
56.6	2.22	18.66	1.764	113.14	51.55	1.12	18.33	2.309	65.21	42.66	0.98	22	0	256.92	32.72	0.54	32
Plot 2a /Level 1 / May						Plot 2a /Level 2 / May						Plot2 a /Level 3 / May					
% M C		kPa		L(cm)	% M C		kPa		L(cm)	% M C		kPa		L(cm)	% M C		L(cm)
56.42	1.92	12	0	276.57	40.61	1.75	38.78	1.528	170.49	31.48	0.81	42.67	1.764	315.86	32.4	1.53	38
68.34	0.52	11.66	0.882	268.71	38.85	2.81	24	2	245.14	34.34	1.53	48.33	1.202	268.71	23.47	2.84	34
67.41	1.03	12.66	2.404	154.78	34.63	0.04	22.33	1.453	326.85	32.61	0.97	47.33	2.404	256.14	24.12	1.93	38
Plot 2a /Level 1 /August						Plot 2a /Level 2 / August						Plot2 a /Level 3 / August					
% M C		kPa		L(cm)	% M C		kPa		L(cm)	% M C		kPa		L(cm)	% M C		L(cm)
69.48	0.94	25.67	3.383	292.28	26.84	1.35	53.67	5.239	209.78	29.31	1.33	65	2	326.86	23.46	0.63	89
62.34	0.6	24.33	1.764	315.85	32.71	3.78	35	1.528	215.28	24.64	5.57	96.33	4.702	331.57	26.28	0.54	88
59.93	1.3	22	1.155	234.14	41.44	0.97	36.33	3.283	242.78	26.5	1.87	39.33	0.667	311.14	18.17	0.11	97
Plot 5a /Level 1 / February						Plot 5a /Level 2 / February						Plot 5a /Level 3 / February					
% M C		kPa		L(cm)	% M C		kPa		L(cm)	% M C		kPa		L(cm)	% M C		L(cm)
92.08	2.76	11.5	1.5	10.21	68.98	2.06	11	0.5	3.92	52.44	0.7	11	0.577	42.43	41.11	1.04	20
35.11	5.09	10	0	9.42	87.14	2.755	8.67	0.667	6.28	68.78	0.64	11	1	26.71	29.85	1.01	34
82.43	2.02	10.67	0.667	8.64	77.76	0.94	12	2	6.28	53.44	1.1	16	2	11	27.44	1.08	22
Plot 5a /Level 1 / May						Plot 5a /Level 2 / May						Plot 5a /Level 3 / May					
% M C		kPa		L(cm)	% M C		kPa		L(cm)	% M C		kPa		L(cm)	% M C		L(cm)
85.33	3.6	11.33	1.202	13.35	60.76	0.14	10.33	1.202	16.49			22.67	3.712	52.64	38.77	0.41	44
59.89	2.66	10.66	1.764	8.64	79.55	1.12	12.5	3.5	14.14	33.87	0.93	21	1	48.71	30.26	0.52	34
70.46	18.5	12	2	11	58.32	0.7	11	1	26.71								
Plot 5a /Level 1 / August						Plot 5a /Level 2 / August						Plot 5a /Level 3 / August					
% M C		kPa		L(cm)	% M C		kPa		L(cm)	% M C		kPa		L(cm)	% M C		L(cm)
68.61	0.73	13.33	1.764	23.6	24.51	0.15	15.33	3.528	94.2	29.86	1.37	38.33	3.383	125.7	25.26	1.67	63.67
46.94	2.01	14	1.155	55	32.86	2.15	18	2	31.4	32.91	2.48	32	0	55	22.13	2.29	57.33
51.64	1.9	12.67	0.667	39.2	22.41	0.333	18.33	0.882	141.4	19.94	3.53	23	3.512	180.7	27.81	1.47	51.33
																	110

Appendix 7a:				
Natural re-vegetation in April 1987 (see Fig. 5a for further details on positions)				
-> Plots --	10a	10b	13a	13b
Position A5	grass (?)	-----none-----	-----none-----	grass spp.
B5	grass	<i>Taraxacum officinale</i>	<i>T. officinale</i>	-----none-----
C5	<i>Carex sp</i>	<i>Rumex sp.</i>	-----none-----	<i>T. officinale</i>
D5	<i>Plantago sp.</i>	<i>Solidago sp.</i>	<i>Carex sp.</i>	<i>T. officinale</i>
A4	<i>T. officinale</i>	<i>T. officinale</i>	<i>T. officinale</i>	-----none-----
B4	grass	---unidentifiable--	Grass	<i>Rumex sp.</i>
C4	<i>Rumex sp.</i>	Grass	<i>T. officinale</i>	<i>Trifolium repens</i>
D4	Grass	<i>T. repens</i>	Grass	<i>T. officinale</i>
A3	-----none-----	<i>Rumex sp.</i>	Grass	Grass
B3	Grass	<i>Rumex sp.</i>	<i>T. officinale</i>	Grass
C3	-----none-----	<i>Solidago sp. (?)</i>	Grass	-----none-----
D3	<i>Rumex sp.</i>	Grass	<i>T. officinale</i>	<i>T. repens</i>
A2	-----none-----	<i>Rumex sp.</i>	Grass	<i>Cirsium sp.</i>
B2	<i>E. hirsutum (?)</i>	-----none-----	Grass	<i>Cirsium sp.</i>
C2	-----none-----	-----none-----	-----none-----	Grass
D2	<i>Rumex sp.</i>	-----none-----	-----none-----	<i>Cirsium sp. (?)</i>
A1	-----none-----	-----none-----	<i>Rumex sp.</i>	-----none-----
B1	-----none-----	Grass	--unidentifiable--	<i>Rumex /Cirsium (?)</i>
C1	-----none-----	<i>Cirsium sp.</i>	-----none-----	Grass
D1	-----none-----	-----none-----	--unidentifiable--	Grass

Appendix 7b :

Natural re-vegetation in September 1987 (see Fig. 5a for further details on positions)

Plots -- ->	10a	10b	13a	13b
Position A5	<i>Poa sp.</i>	<i>Poa sp.-</i>	<i>Grass (Festuca sp.(?)-</i>	<i>Poa sp.</i>
B5	<i>Poa sp.</i>	<i>Carex sp.</i>	<i>Poa sp.</i>	<i>Bromus sp.</i>
C5	<i>Carex sp.</i>	<i>Bromus sp. .</i>	<i>Festuca sp.</i>	<i>Poa sp.</i>
D5	<i>Plantago major</i>	<i>Solidago sp.</i>	<i>Carex sp.</i>	-----none-----
A4	<i>Taraxucum officinale</i>	<i>Trifolium repens</i>	<i>Scrophularia sp.</i>	<i>Carduus sp.</i>
B4	<i>Poa sp.</i>	<i>Galium aparine</i>	<i>Poa sp.</i>	<i>Rumex sp.</i>
C4	<i>Rumex sp</i>	<i>Cirsium sp.</i>	<i>Carduus sp.</i>	<i>Trifolium repsens</i>
D4	<i>Scrophularia sp.</i>	<i>Ranunculus repens</i>	<i>Poa sp.</i>	-----none-----
A3	<i>Viola sp.</i>	<i>Taraxacum sp.</i>	<i>Cardus sp.</i>	<i>Cirsium sp.</i>
B3	<i>Apium nodiflorum</i>	<i>Arrhenatherum elatius</i>	<i>Veronica sp.</i>	<i>Potentilla sp (?)</i>
C3	<i>Cirsium sp.</i>	<i>Carduus sp.</i>	<i>Grass /Glyceria sp.(?)</i>	<i>Lycopus europaeus</i>
D3	<i>Veronica sp.</i>	<i>Lychnis flos-cuculi</i>	<i>Poa sp.</i>	<i>Trifolium repens</i>
A2	<i>Scrophularia sp</i>	<i>Veronica sp.</i>	-----none-----	<i>Rumex sp.</i>
B2	-----none-----	<i>Rumex sp.</i>	<i>Glyceria sp.</i>	<i>Cirsium sp.</i>
C2	<i>Veronica sp.</i>	<i>Veronica sp.</i>	<i>Lycopus europaeus</i>	<i>Rumex sp.</i>
D2	<i>Rumex sp.</i>	<i>Grass (Glyceria ?)</i>	<i>Lycopus europaeus</i>	<i>Rumex sp.</i>
A1	<i>Veronica sp.</i>	<i>Rumex sp.</i>	<i>Veronica sp.</i>	<i>Mentha aquatica</i>
B1	<i>Glyceria maxima</i>	<i>Ranunculus sceleratus</i>	-----none-----	<i>Veronica sp.</i>
C1	<i>Cirsium sp.</i>	<i>Rumex sp.</i>	<i>Grass (Glyceria ?)</i>	-----none-----
D1	<i>Veronica sp.</i>	-----none-----	<i>Grass (Glyceria ?)</i>	-----none-----

Appendix 7c				
Natural re-vegetation in May 1988 (see Fig. 5a for further details on positions)				
Plots -- ->	10a	10b	13a	13b
Position A5	<i>Rumex sp.</i>	<i>Grass (?)</i>	<i>Poa sp.</i>	<i>Grass sp.</i>
B5	<i>Festuca sp.</i>	<i>Juncus sp.</i>	<i>Galium sp.</i>	<i>Apium (?)</i>
C5	<i>Senecio vulgaris</i>	<i>Poa sp.</i>	<i>Bromus sp.</i>	<i>Grass (?)</i>
D5	<i>Bromus sp.</i>	<i>Poa sp.</i>	<i>Grass (?)</i>	<i>Galium sp.</i>
A4	<i>Carex sp.</i>	<i>Grass (?)</i>	<i>Poa sp.</i>	<i>Taraxacum officinale</i>
B4	<i>Geranium sp.</i>	<i>Solidago sp.</i>	<i>Epilobium hirsutum</i>	<i>Poa sp.</i>
C4	<i>Rumex sp.</i>	<i>Carduus sp.</i>	<i>Arrhenatherum elatius</i>	<i>Cirsium arvense</i>
D4	<i>Dactylis glomerata</i>	<i>Agrostis sp.</i>	<i>Rumex sp.</i>	<i>Cirsium sp.</i>
A3	<i>Impatiens glandulifera</i>	<i>E. hirsutum</i>	<i>Gallium sp.</i>	<i>Rumex sp.</i>
B3	<i>Carduus sp.</i>	<i>Grass (?)</i>	<i>Rumex sp.</i>	<i>Solanum sp.</i>
C3	<i>Cirsium sp.</i>	<i>Carduus sp.</i>	<i>Grass (Glyceria sp.?)</i>	<i>Lycopus europaeus</i>
D3	<i>Sysymbrium officinale</i>	<i>Agrostis sp.</i>	<i>Festuca sp.</i>	<i>Heracleum sp.</i>
A2	<i>Apium nodiflorum</i>	<i>Carduus sp.</i>	<i>Filipendula ulmaria</i>	<i>Grass (Poa sp.?)</i>
B2	<i>Carduus sp.</i>	<i>Solidago sp.</i>	<i>Rumex sp.</i>	<i>Rumex sp.</i>
C2	<i>Rumex sp.</i>	<i>Glyceria sp.</i>	<i>Rumex sp.</i>	<i>Cirsium sp.</i>
D2	<i>Cirsium sp.</i>	<i>Carduus sp.</i>	<i>Cirsium sp.</i>	<i>Rumex sp.</i>
A1	<i>Veronica sp.</i>	<i>Glyceria sp.</i>	<i>Cirsium sp.</i>	<i>Glyceria aquatica</i>
B1	<i>Juncus sp.</i>	<i>Glyceria maxima</i>	<i>Juncus sp.</i>	<i>Cirsium arvense</i>
C1	<i>Juncus sp.</i>	<i>Apium nodiflorum</i>	<i>Cirsium arvense</i>	<i>Solidago sp.</i>
D1	<i>Rumex sp.</i>	<i>Solidago sp.</i>	<i>Juncus sp.</i>	<i>Cirsium sp.</i>

Appendix 8: Sample of Raw Erosion Data (Natural re-vegetation Plots No. 10b & No. 13a)

Plot 10b

Plot 13a

	GJ	OK	GL	GM	GN	OO	GP	OO	GR	GS	GT	GU	GV	GW	GX	GZ	HA
	E 1.0m	R 1.5m	O 2.0m	S 2.5m	I 3.0m	Q 3.5m	N 4.0m			E 1.0m	R 1.5m	O 2.0m	S 2.5m	I 3.0m	Q 3.5m	N 4.0m	
Aug-86	mm	mm	mm	mm	mm	mm	mm			mm	mm	mm	mm	mm	mm	mm	
200cm										200cm							
150cm										150cm							
100cm										100cm							
50cm										50cm							
Sep-86										Sep-86							
200cm										200cm							
150cm										150cm							
100cm										100cm							
50cm										50cm							
Oct-86										Oct-86							
200cm										200cm							
150cm										150cm							
100cm										100cm							
50cm										50cm							
Nov-86										Nov-86							
200cm										200cm							
150cm										150cm							
100cm										100cm							
50cm										50cm							
Dec-86										Dec-86							
200cm										200cm							
150cm										150cm							
100cm										100cm							
50cm										50cm							
Jan-87										Jan-87							
200cm										200cm							
150cm										150cm							
100cm										100cm							
50cm										50cm							
Feb-87										Feb-87							
200cm										200cm							
150cm										150cm							
100cm										100cm							
50cm										50cm							
Mar-87										Mar-87							
200cm										200cm							
150cm										150cm							
100cm										100cm							
50cm										50cm							
Apr-87										Apr-87							
200cm										200cm							
150cm										150cm							
100cm										100cm							
50cm										50cm							
May-87										May-87							
200cm										200cm							
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Jun-87										Jun-87							
200cm										200cm							
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Jul-87										Jul-87							
200cm										200cm							
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Aug-87										Aug-87							
200cm										200cm							
150cm										150cm							
100cm										100cm							
50cm										50cm							
Sep-87										Sep-87							
200cm										200cm							
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Oct-87										Oct-87							
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Nov-87										Nov-87							
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Dec-87										Dec-87							
200cm										200cm							
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50cm										50cm							
Jan-88										Jan-88							
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Feb-88										Feb-88							
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Mar-88										Mar-88							
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Apr-88										Apr-88							
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May-88										May-88							
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Jun-88										Jun-88							
200cm										200cm							
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100cm										100cm							
50cm										50cm							
Jul-88										Jul-88							
200cm										200cm							
150cm										150cm							
100cm										100cm							
50cm										50cm							

Appendix 9: Soil Analysis Results							
Treatment	Plot No.	Sample Position (height from Bank- ¹ % Sand	Particle	Size % Silt	Class % Clay	Bulk Density (kg/l)	
Bare	1a	0.8m	62	14	24	1.02	
		1.75m	65	12	23	0.96	
Bare	1b	0.8m	67	9	24	1.02	
		1.75m	53	14	33	0.98	
Natural Vegetation	8a	0.8m	55	17	28	1.1	
		1.75m	53	18	29	0.98	
Natural Vegetation	8b	0.8m	56	14	30	1.02	
		1.75m	53	21	26	1.01	
Bare	15a	0.8m	67	14	19	0.96	
		1.75m	63	11	26	0.96	
Bare	15b	0.8m	71	11	18	1.02	
		1.75m	68	9	23	1.01	
NB:							
Bare plots were obtained by application of herbicide to previously naturally vegetated banks.							
Plots 15a & 15b were allocated for seeding with <i>Phalaris arundinacea</i>							